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NONDESTRUCTIVE INSPECTION OF SHELTER
PANELS

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General American Transportation
Corporation

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FOREWORD

This report was prepared by General American Transportation Corporation (GATX), General American Research Division (GARD), for the Air Force Civil Engineering Center, Tyndall AFB, Florida, under contract F-33615-71-C-1552, with the Air Force Materials Laboratory, Wright-Patterson AFB, Ohio. The job order number was 2054 02 04. The work was performed under the guidance of J. Robert Van Orman, AFCEC/DE. The technical representatives on the contract during the first and second phases of the effort, were R. R. Rowand, AFML-LLN, and Grover Hardy, AFML-MXA, respectively.

The work was performed at GARD in the NDT and Diagnostic Systems Group, W. Lichodziejewski, Group Leader, by Irvin R. Kraska, Project Engineer and Principle Investigator, with the assistance of Ronald G. Prusinski and John J. Wolfe, NDT Engineers. The authors gratefully acknowledge the assistance provided by Headquarters Tactical Air Command and Lt Col Charles H. Hartman, Major Robert C. Raisons, Capt David L. MacHeel, and TSgt J. K. Deem during the performance of field tests conducted at Holloman Air Force Base and providing the shelters used for the laboratory investigation.

This report summarizes work done starting September 1973 through November 1974. An interim report, AFCEC-TR-74-3, was published in May 1974 covering the development of the functional model.

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This report has been reviewed by the Information Officer (IO) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved.

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ABSTRACT

Debonds and free water presence are defects common to air transportable Air Force shelters of laminated panel construction. Reliable and early field detection of both types of defects is required for efficient field maintenance of the shelters, particularly for those which are field expandable. No appropriate defect inspection technology is currently available to maintenance personnel. Therefore, the development program described herein was undertaken to provide simple nondestructive inspection equipment and corresponding inspection procedures.

In this program, a broad spectrum of nondestructive testing methods was evaluated for sensitivity to debond and free water in each of six panel configurations: both metal and fiberglass facing materials bonded to paper honeycomb, balsa wood, and foam cores. It was found that a combination of three techniques is required to reliably inspect the six configurations. To allow simultaneous inspection for debonds and water in panels with metal facing sheets (90% of the sample population) a unique eddy sonic technique was developed. For water detection in fiberglass faced panels with paper honeycomb cores, a high frequency pitch-catch ultrasonic technique was developed. For the remaining water and debond inspection of fiberglass-faced panels, a low frequency pitch-catch ultrasonic technique was developed. The eddy sonics technique has demonstrated the capability for detection of 1/2" diameter and larger debonds in foam core panels with from 0.020" to 0.100" metal face sheet thicknesses. The technique is further capable of detecting a single water-filled cell in metal-to-paper honeycomb panels, as well as a 1" diameter by .020" thick water-filled area in metal-to-foam panels. Approximate inspection rates of 600 square feet per hour were obtained for the system while maintaining sensitivity to 2" diameter debonds.

The high frequency pitch-catch ultrasonic technique has demonstrated the capability to detect 1/4" diameter by 1/2" thick water-filled cells in fiberglass-faced panels with paper honeycomb cores, with an approximate scan rate of 200 square feet per hour. The reduction of the scan rate for this method from that obtained with the eddy sonics technique is primarily attributed to the necessity for use of a liquid acoustic couplant.

The low frequency pitch-catch ultrasonic inspection technique has shown reliable capability for the detection of 1" diameter debond and water conditions in the remainder of fiberglass-faced panels, with a scan rate of approximately 400 square feet per hour. Although no liquid acoustic couplant is required for operation, a reduced scan rate from that of the eddy sonic method results from the more careful physical manipulation required by spring-loaded point contact probe design. Each of the three techniques has undergone successful laboratory and field evaluations.

In Phase II, functional models based upon the successful work in Phase I were designed, fabricated and field tested. Inspection procedures for equipment field use were developed. Training of CEC operating personnel was accomplished. An Operating Manual was written.

Each of the NDT techniques met, or exceeded, the inspection requirements for detection of debond and water defect conditions in shelter panels. The field evaluation provided valuable input for future improvements to the operational characteristics, size and weight of production models. Better control of coil wave form is required and finer control over oscillator output voltage is also needed. To obtain these desired goals tight specifications on purchased components need to be written.

Several field inspections have been performed. The results and the modifications to the original equipment have produced an operational, field ready, system configuration. However, the system is bulky and heavy (about 30" X 21" X 29" and 200 lbs. with batteries; 120 lbs without batteries). It is recommended that future units undergo miniaturization to reduce both size, weight, and improved operational characteristics. Depending upon the number of production units required, a miniaturization program could be cost effective. It is estimated that the weight and bulk can be reduced to 1/4 its present size.

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SECTION I

OBJECTIVE

The objective of this program is to provide maintenance personnel with a simple nondestructive inspection capability, and related inspection procedures, for field detection of debonds and water in shelter sandwich panels composed of either metal or fiberglass facing sheets joined to resin impregnated paper honeycomb, balsawood, or foam cores.

SECTION II

SUMMARY AND CONCLUSIONS

The materials, construction, and utilization of sandwich panels in air transportable shelters have been studied with respect to the use of nondestructive testing methods for field inspection by maintenance personnel. Two types of defects have been studied: delaminations and excessive moisture. Defect prominence, modes of panel failure, and definition of inspection constraints have been established by four separate on-site investigations of field conditions. Numerous nondestructive inspection techniques have been studied qualitatively, and several were evaluated under laboratory conditions.

It has been concluded and test verified that a unique eddy sonics scanning approach can provide field capability for detection of defects in the majority of panels in use. These panels consist of metal facing sheets bonded to foam, balsa, and paper honeycomb cores. For fiberglass-faced panels, a high frequency pitch-catch ultrasonic sampling method is suitable for detecting moisture in paper honeycomb core panels, and a low frequency pitch-catch ultrasonic scanning technique will detect moisture in the foam and balsa cores. The low frequency ultrasonic unit can also be used to detect debonds in all fiberglass-faced panels.

In Phase II, functional models based upon the successful work in Phase I were designed, fabricated and field tested. Inspection procedures for equipment field use were developed. Training of CEC operating personnel was accomplished. An Operating Manual was written.

Each of the NDT techniques met, or exceeded, the inspection requirements for detection of debond and water defect conditions in shelter panels.

SECTION III

RECOMMENDATIONS

Three nondestructive testing methods are recommended to allow the desired inspection capability for the six types of shelter sandwich panels. The inspection methods and their applications are:

1. Frequency Counting Eddy Sonics is recommended for both debond and water detection in metal-to-paper honeycomb, metal-to-balsawood, and metal-to-foam panels.
2. Low Frequency Pitch-Catch Ultrasonics is recommended for debond detection in fiberglass-to-paper honeycomb, fiberglass-to-foam, and fiberglass-to-balsawood panels. It is also recommended for water detection in fiberglass-to-balsawood and fiberglass-to-foam panels.
3. High Frequency Pitch-Catch Ultrasonics is recommended for water detection in fiberglass-to-paper honeycomb panels. It can also be used as a back-up technique for water detection in metal-to-paper honeycomb panels.

The field evaluation provided valuable input for future improvements to the operational characteristics, size and weight of production models. Better control of coil wave form is required and finer control over oscillator output voltage is also needed. To obtain these desired goals tight specifications on purchased components need to be written.

Several field inspections have been performed. The results and the modifications to the original equipment have produced an operational, field ready, system configuration. However, the system is bulky and heavy (about 30" X 21" X 29" and 200 lbs. with batteries; 120 lbs without batteries). It is recommended that future units undergo miniaturization to reduce both size, weight and improved operational characteristics. Depending upon the number of production units required, a miniaturization program could be cost effective. It is estimated that the weight and bulk can be reduced to 1/4 its present size.

SECTION IV

PROBLEM DEFINITION

4.1 Introduction

Air transportable shelters are employed by the Air Force in a variety of configurations for mobile housing and storage facilities. (See Figure 1.) Collapsible design and lightweight, sandwich-panel construction combine to provide optimum flexibility for the implementation of shelters as temporary field hospitals, instrumentation storage and maintenance facilities, etc. This design flexibility and portability subjects shelters to frequent transportation and operational and environmental extremes which contribute to reduction in individual shelter integrity. The manpower and facilities for maintenance of shelter panel integrity are primarily employed for rework and repair of gross panel delaminations caused by debond and/or water, since no procedures or instrumentation have been available for early defect detection.

This program is directed towards the development of inspection methods and procedures to reduce the amount of rework on shelters by early detection of shelter panel defects. To accomplish these objectives, information to define the problem and user needs was collected from four shelter users. Analysis of nondestructive methods to determine techniques applicable to the problem was conducted. Then an inspection philosophy was developed based upon knowledge of shelter panel materials, panel failure modes, and Air Force constraints. Appropriate selected NDI methods were evaluated under laboratory conditions with panel materials provided by the Air Force. The initial laboratory evaluations were conducted on cut-out sections of panels to determine the major candidate techniques. These techniques were then evaluated, on a supplied shelter, for sensitivity to the effects of compositional variations (e.g., voids in the adhesive layer, panel surface conditions, and adhesive layer thicknesses, etc.). The most effective inspection techniques were then field-tested in bread-board configurations to demonstrate their applicability to the problem.

The body of this report contains (a) those constraints which have determined the inspection philosophy which has been adopted, and (b) descriptions of the techniques which were demonstrated as acceptable by

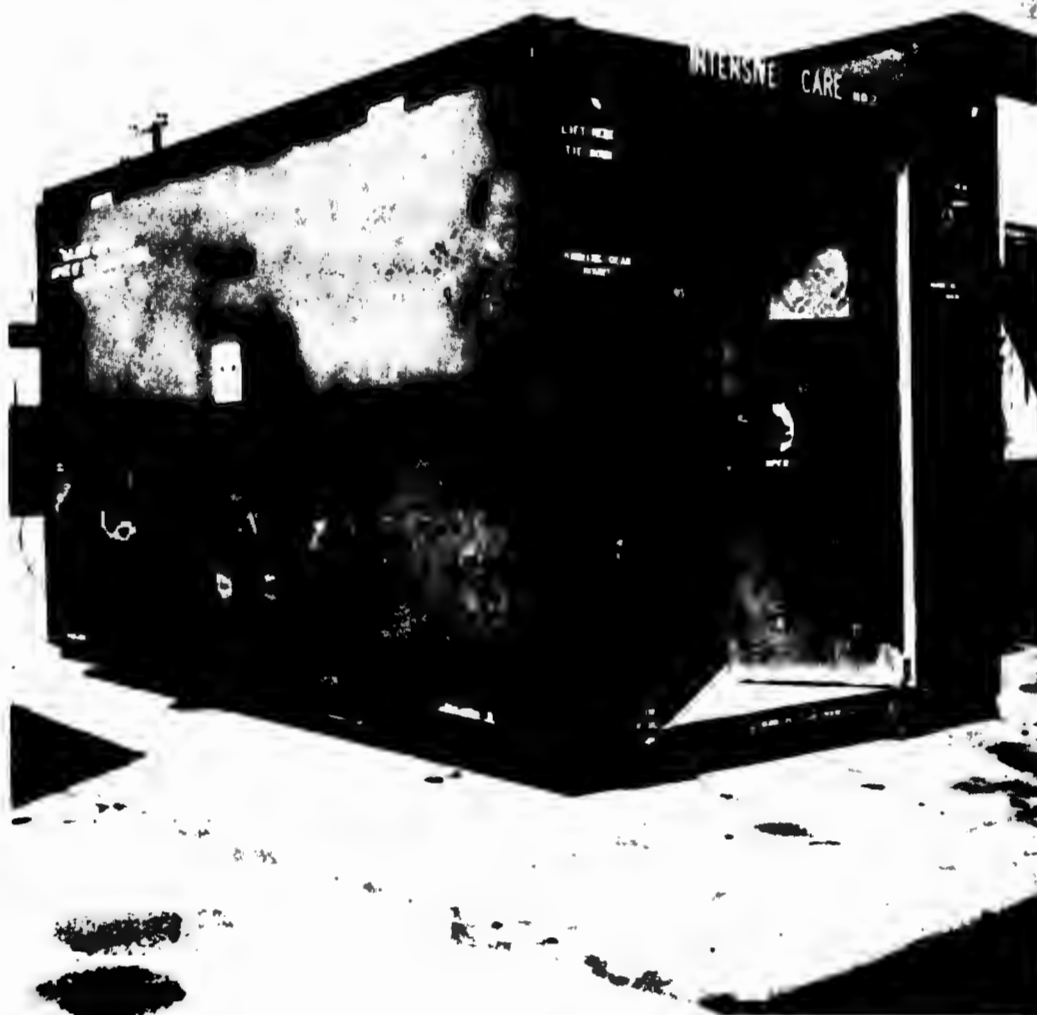


Figure 1 EXPANDABLE SHELTER USED FOR FIELD HOSPITAL

successfully meeting field inspection requirements. The Appendices contain (a) a qualitative analysis to identify potentially applicable nondestructive tests, and (b) the results of the laboratory evaluation of instrumentation utilizing the potentially applicable tests. The remainder of this section details those considerations used to develop the pertinent inspection philosophy.

4.2 Shelter Panel Compositions

The combinations of materials used in shelter panel fabrication of concern to this program include two types of facing material (metal and fiberglass) and three types of core material (paper honeycomb, balsa wood, and foam). These material selections enable definition of six different types of shelter panel construction:

- a) Metal facing-to-paper honeycomb core (32% of total sample population)
- b) Metal facing-to-balsa wood core (4% of total sample population)
- c) Metal facing-to-foam core (54% of total sample population)
- d) Fiberglass facing-to-paper honeycomb core (5% of sample population)
- e) Fiberglass facing-to-balsa wood core (3% of sample population), and
- f) Fiberglass facing-to-foam core (2% of total sample population).

4.3 Failure Modes

Observations of the modes of shelter panel failure were made by surveying shelters at each of four shelter locations:

- a) 4449th Mobility Support Squadron, Holloman Air Force Base
- b) 12th Training Flying Wing (Air Traffic Control Systems, NAVAID Maintenance), Randolph Air Force Base
- c) 727th Tactical Control Squadron, Bergstrom Air Force Base, and
- d) 41st Combat Support Hospital, Fort Sam Houston.

The common defect conditions encountered were observed to be debond, or delamination of the panel facing material from the adhesive layer (which, itself, generally remained bonded to the core material), the presence of water in contact with the inside surface of a debonded face sheet, water present in both single cells and groups of cells in honeycomb core materials, and gross amounts of water filling the complete interior of the sandwich between the two face sheets.

Almost no interior panel surface debond was observed on shelters stored in the collapsed condition, while both interior and exterior panel surface debond was found on shelters stored in the expanded configuration. Many of these debonds were observed to extend from, and along, the panel edges presenting a "picture-frame" visual effect.

Water, when present, generally was associated with the described panel edge debond condition. This observation is significant with respect to determination of shelter panel inspection requirements in that panel defect inspection priority may be assigned to debond detection. Should reliable and early debond detection consistently restrict defect initiation to panel edges, simplified maintenance procedures and improved inspection procedures could result. It is, however, possible that a closed debond area, such as a void in the adhesive layer in the center of a panel could ultimately affect shelter panel structural integrity. Handling, or even routine usage, of the shelter facility could introduce sufficient stresses to cause such a debond to grow outward to panel edges. If such center outgrowth does occur, then 100% panel scanning for debonds will always be required, and simplified "picture-frame" scanning cannot be used.

4.4 Inspection Constraints

The foregoing subsections have listed panel materials and have outlined the type, location, and incidence of defects. Air Force constraints of simplicity, high inspection speed, ease of operation, reliability, cost, and short project duration imply the use of existing NDT techniques incorporating rugged, commercially-available instrumentation. An obvious additional criteria for optimization of inspectability is the need for a minimum number of techniques to inspect all the panel configurations. The cumulative analysis of the material, failure modes, and the inspection constraints has resulted in the following inspection philosophy.

4.5 Inspection Philosophy

Detection of the panel defects listed below in terms of size and location has been established as basic to fulfilling maintenance requirements:

1. Detection of 2" diameter near side debonds by 100% scanning on exterior panel surfaces exposed to the environment, and
2. Detection of 2" diameter near side debonds by 100% scanning on interior panel surface of open shelters which received rough abuse.

In addition to the definition of defect conditions, practical considerations for implementation of the inspection method have been determined to include ease and reliability of operation of inspection equipment and procedures, minimization of operator-sensitive variables (liquid couplants, data interpretation, etc.), high rates of inspection and simple, portable inspection instrumentation.

Evaluation of the types of materials to be inspected, the nature of defects required to be detected, and the field conditions under which the inspections must be performed have limited the inspection methods which can fulfill the program objectives. The appendices following the report describe: (a) qualitative analysis of potentially applicable nondestructive tests, and (b) results of the laboratory evaluation of the qualitatively established potentially applicable tests.

The following section describes the methods selected for field evaluation, discusses theories of operation, and presents representative field inspection results.

SECTION V

SELECTED INSPECTION SUMMARY

Various NDT methods were qualitatively considered for inspection of shelter sandwich panels. Those selected as potentially applicable were subjected to initial laboratory evaluations on panel sections removed from a Bare Base shelter. Final laboratory evaluations were conducted on panels in place on a shelter. Appendix A of this report describes the qualitative analyses performed in selection of candidate techniques for laboratory evaluations. Appendix B details the laboratory evaluations. This section of the report provides information on the applicability of three field proven techniques which survived the laboratory tests, theoretical discussion of their operation, and typical field inspection results. These three techniques, together, fulfill the inspection requirement which generated this program.

5.1 Inspection Summary

The inspection techniques selected as fulfilling the inspection requirements for this program are presented in Table I. It lists the panel compositions and shows the inspection methods found to reliably detect debonds and water in them. The inspection methods are obviously divided into two general facing sheet application categories - metallic and nonmetallic. One inspection method, Frequency Counting Eddy Sonics is used to inspect all metallic panels, which constitute about 90% the panels in use. The remaining panels (approximately 10%) are inspected with the other two methods. As a result, bases which do not have non-metallic shelter panels would not be required to have all pieces of inspection equipment. Thus, equipment logistics and inspector education could be greatly reduced. The three inspection methods are described in detail in the following sections.

5.2 Frequency Counting Eddy Sonics

The Eddy Sonics test method is based on the phenomenon that a mechanical force is inherently associated with the flow of eddy currents. Since the eddy current field is time-variant, the mechanical force is also time-variant. Thus, an acoustic vibration can be induced in the proper sample.

TABLE I. SHELTER PANEL INSPECTION METHODS

PANEL COMPOSITION INSPECTION METHOD

PANEL COMPOSITION		INSPECTION METHOD	
Facing Sheet	Core	Debonds	Water
Metal	Paper Honeycomb	Frequency Counting Eddy Sonics	Frequency Counting ² Eddy Sonics
	Balsawood	Frequency Counting Eddy Sonics	Frequency Counting ³ Eddy Sonics
	Foam	Frequency Counting Eddy Sonics	Frequency Counting ³ Eddy Sonics
Fiberglass	Paper Honeycomb	Low Frequency Pitch-Catch Ultrasonics	High Frequency Pitch-Catch Ultrasonics
	Balsawood	Low Frequency Pitch-Catch ¹ Ultrasonics	Low Frequency Pitch-Catch Ultrasonics
	Foam	Low Frequency Pitch-Catch ¹ Ultrasonics	Low Frequency Pitch-Catch ¹ Ultrasonics

1. Haven't encountered such panels in field or lab; expect technique would work.
2. High frequency pitch-catch ultrasonics can be used as a back-up technique for water detection.
3. Low frequency pitch-catch ultrasonics can be used as a back-up technique for water detection.

To employ the Eddy Sonics principle as a nondestructive method for inspection of sandwich materials some constituent of the system must be electrically conductive. This is a disadvantage with respect to the range of potential applications in shelter panel materials. However, this standard Eddy Sonics test does fulfill the inspection requirements for more than 90% of panel compositions as shown in Table I.

A commercially available Eddy Sonics inspection instrument (Shurtronics Harmonic Bond Tester) operates on the principle of pulsed Eddy Sonics testing. The frequency of the electrical exciting current applied to the probe coil is 15 kHz, and it is pulsed at 60 Hz. Vibrations produced in the probe and the structures are a result of attractions of both positive and negative electrical current maximums. As a result, the frequency of the mechanical vibrations is 30 kHz.

A highly selective microphone in the probe, coaxial with the coil, measures the vibration response of the panel. This signal is then filtered to reject frequencies below 25 kHz so that the large exciting energy has no effect on the receiver. The signal is then displayed on a meter in either one of two modes. A log scale displays all signal strengths from the lowest value, where the panel is sound, to the highest value, that of a debonded top sheet. A linear scale provides a 10X magnification for greater resolution in various applications.

The major difference between standard application of Eddy Sonics inspection, as described above and that required for shelter panels, is that in shelter panels we wish to inspect for two conditions, both debond and water, simultaneously. While this may appear easy to do by use of the log scale, it is complicated by a) the small voids present in the adhesive (as described in Appendix B) in foam, b) the large size cells in honeycomb cores, and c) the fact that only one constituent of a panel is electrically conductive. These variables reduce the techniques' resultant signal-to-noise ratio.

Based upon the above constraints, it was necessary to modify the Shurtronics Eddy Sonics system to enhance the S/N ratio and make the Eddy Sonic inspection approach viable. It was decided to use a preset frequency counting detection technique to achieve this.

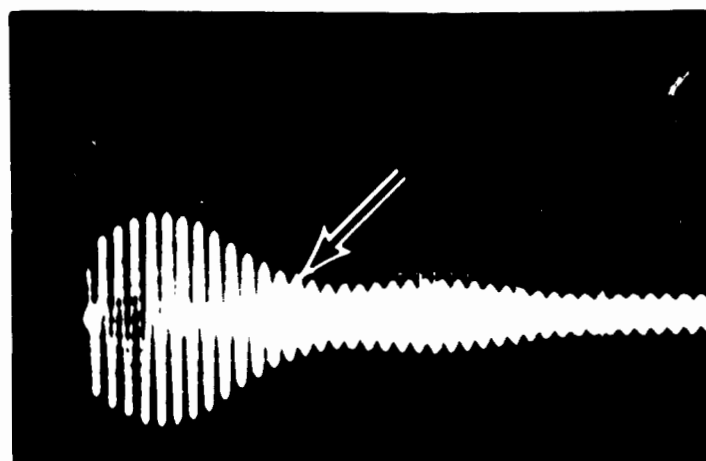
Typical RF Shurtronics oscilloscope patterns from bond, debond and water conditions in a panel are shown in Figure 2. Compare the signal for a bond condition with a debond or presence of water condition. The signal envelope is much longer for the debond than for a bond, and the signal envelope is much shorter for the presence of water than for a bond. Therefore, it was expected that individual pulse counting within the envelope in conjunction with an amplitude threshold could be used to measure envelope damping and we could detect all three conditions (and thus discriminate between them) with one inspection.

Figure 3 shows typical RF patterns for bond and voids, indicating the relative background noise effects which can limit inspection sensitivity. Comparison of the patterns show that the amplitude of the output envelope is strongly influenced by small voids in the adhesive layer. However, the envelope damping is much less influenced. A better signal-to-noise ratio is, therefore, expected with an inspection system which is counter based than one which depends solely on signal amplitude sensing.

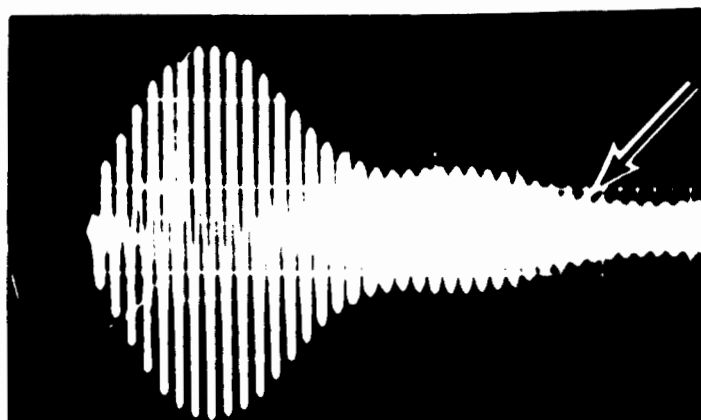
To validate the fact that bonds, debonds, and water can be detected, discriminated, and reliably displayed on a counter readout, aluminum/foam panel inspection is described below.

The Frequency Counting Eddy Sonic inspection equipment used is shown in Figure 4. Briefly, it consists of a Shurtronics Harmonic Bond Tester, a KhronHite filter, and a modified Hewlett Packard Frequency Counter Model 5330B. Used together, the equipment works as described below.

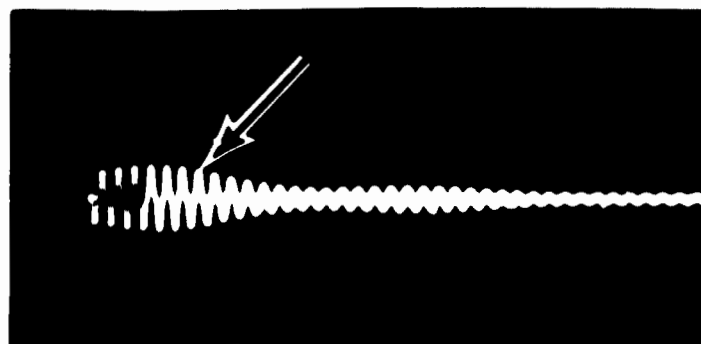
In this case, only the signal generator and receiver portions of the Harmonic Bond Tester are used. The output signal is processed through the filter which rejects all frequencies below 25 kHz so that the larger exciting energy has no effect on the receiver and reduces background noise. The Frequency Counter measures the wave train pulses which exceed a preset amplitude threshold within a preset time base. It contains a digital readout for visual display of the counts made. In addition, the counter also provides dual limit detection which enables selection of both an upper and a lower count limit with the number of counts proportional to the length of the counted wave train.



BOND CONDITION

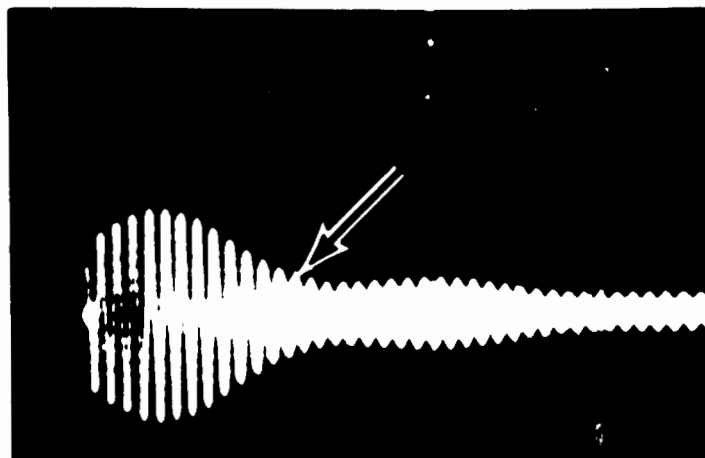


DEBOND CONDITION

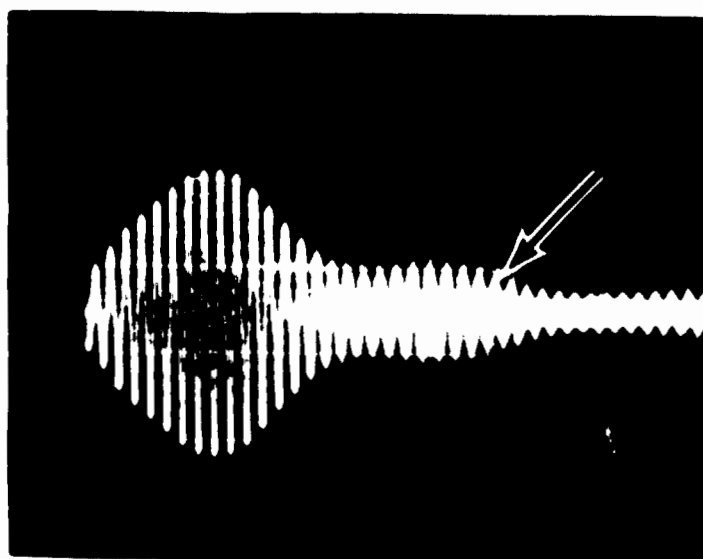


WATER CONDITION

Figure 2 OSCILLOSCOPE DISPLAY OF EDDY SONICS OUTPUT SIGNAL FOR BOND, DEBOND, AND WATER



BOND CONDITION



ADHESIVE VOID CONDITION

Figure 3 OSCILLOSCOPE DISPLAY OF EDDY SONICS OUTPUT SIGNAL
FOR BOND AND VOIDS

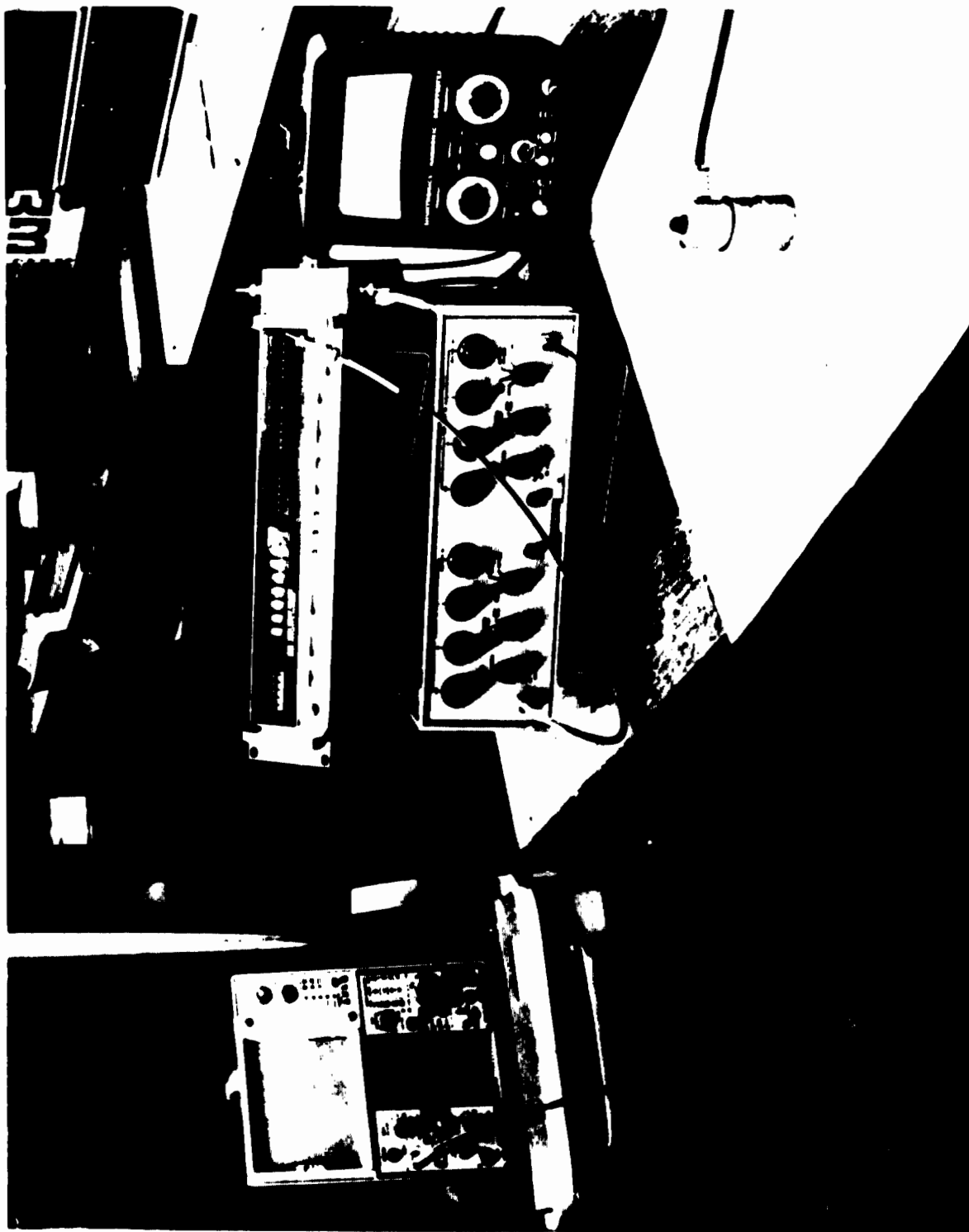


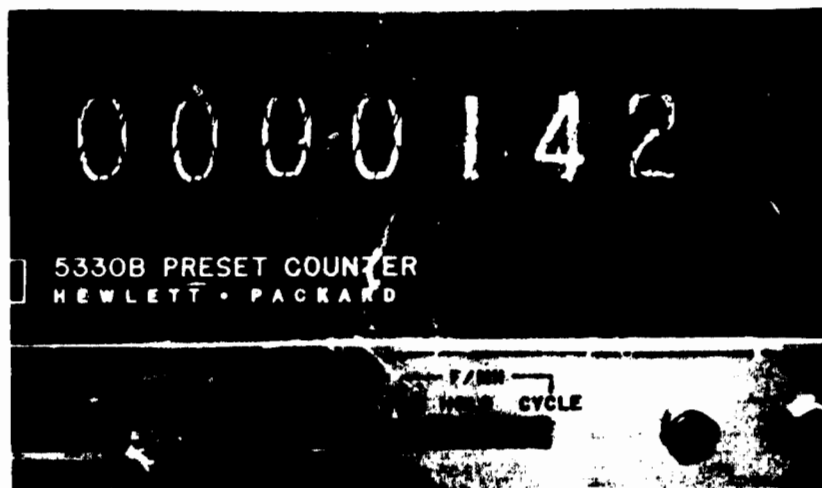
Figure 4 FREQUENCY COUNTING EDDY SONICS INSPECTION EQUIPMENT

This arrangement was used to obtain the photographs shown in Figure 5. These photographs illustrate the change in counts due to bond, debond, and water conditions. The photograph in Figure 5a shows the Eddy Sonic output due to the presence a debond. The photograph is 5b shows the Eddy Sonics output from a bond. Figure 5c shows the signal due to water presence.

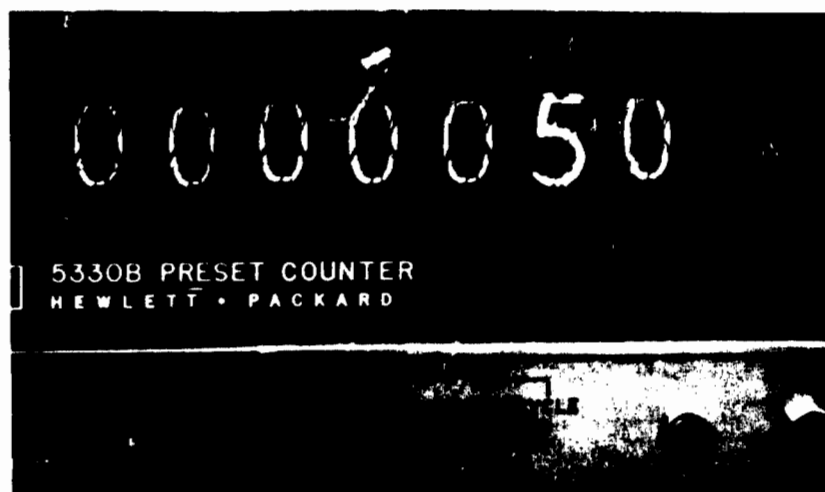
As stated previously, upper and lower limits are presentable on the counter. When they are exceeded, the corresponding HI or LO lamp of the counter display is illuminated. Count rates within the present limits illuminate the IN lamp. High count rates correspond to debond and low count rates correspond to water. The HI, IN, and LO lamps thereby eliminate the need for data interpretation by the operator and immediately thus provide a GO/NO GO panel inspection system. In summary, with Frequency Counting Eddy Sonics, the following results have been achieved. The noise generated by voids has been reduced, the debond and water presence signal-to-noise ratio has been increased, and the detection of debonds and water can be accomplished with one inspection.

The Eddy Sonics inspection method reacts differently to various panel compositions. Certain structures give indications which are the inverse of those observed on other panels. For honeycomb core panels, these situations normally occur where the cell size-to-face sheet thickness ratio is approximately 10 to 1. Local vibrations occur in each cell so that a maximum response is observed in the center of the cell and a minimum response is observed at the cell wall. The general vibration response of a debond will usually be less than that found at the center of a well bonded cell, but can be more, or less, than the response found at the cell wall depending on the particular structure.

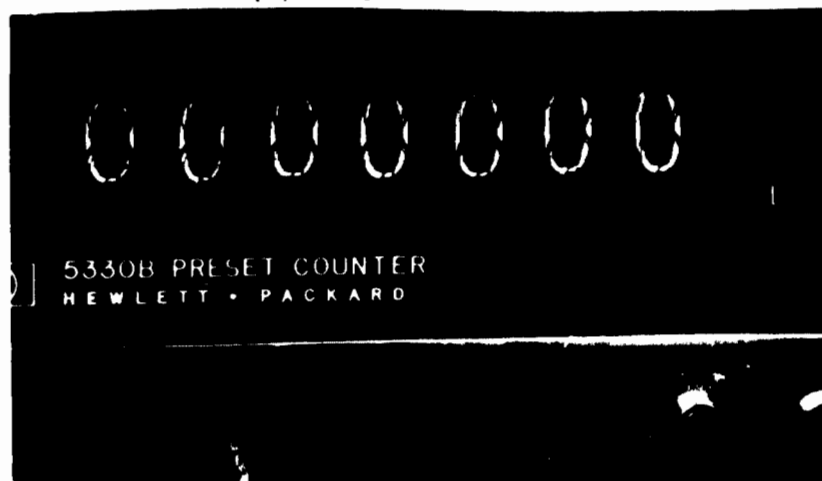
Figure 6 is a typical RF oscilloscope pattern of a bond and debond which illustrates the above point. It shows the change in signal as the probe moves from bond over a cell wall, to bond over the center of the cell, to a debond, and finally to water. The difference in amplitude is apparent between a bond over the cell wall and a bond over the center of a cell. However, the amplitude difference between a debond and a bond over the cell wall is less distinct. Therefore, using strictly amplitude measurement, it is very difficult to differentiate between the two conditions and debond detection would be unlikely in this case on a productive basis.



(a) DEBOND CONDITION

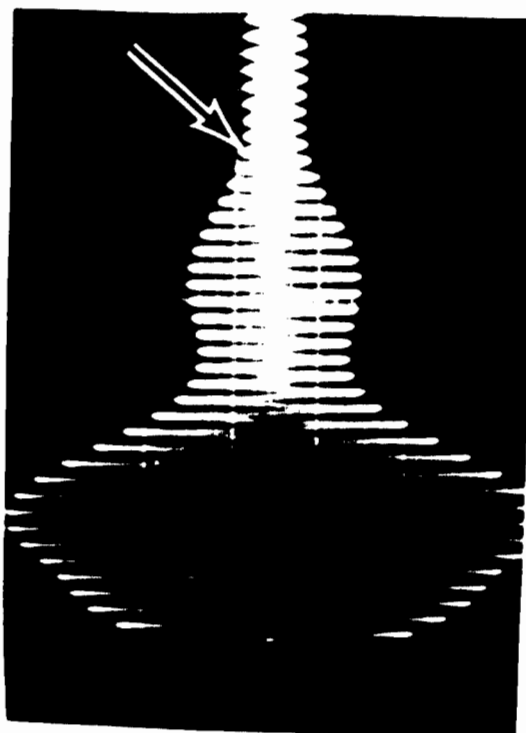


(b) BOND CONDITION

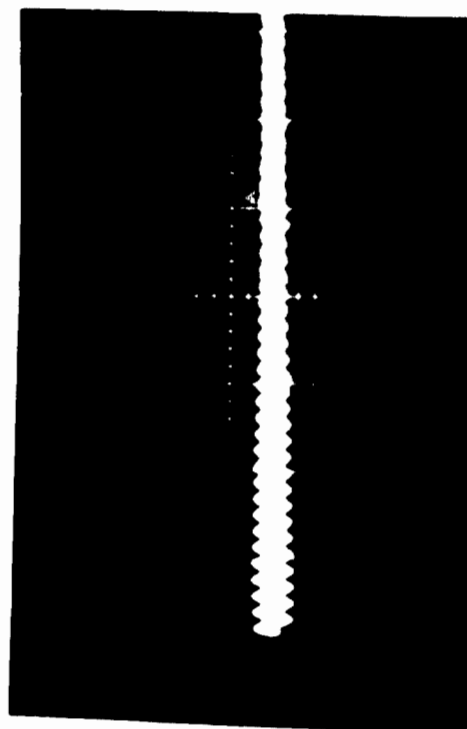


(c) WATER CONDITION

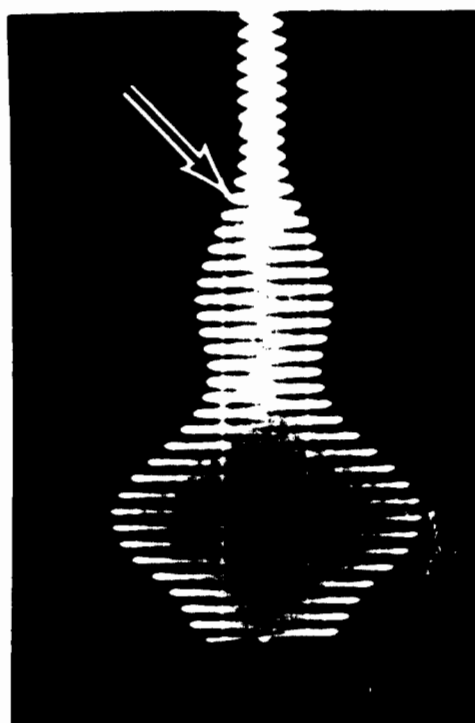
Figure 5 PHOTOGRAPHS OF THE CHANGE IN FREQUENCY COUNTER READINGS DUE TO A DEBOND, BOND AND WATER



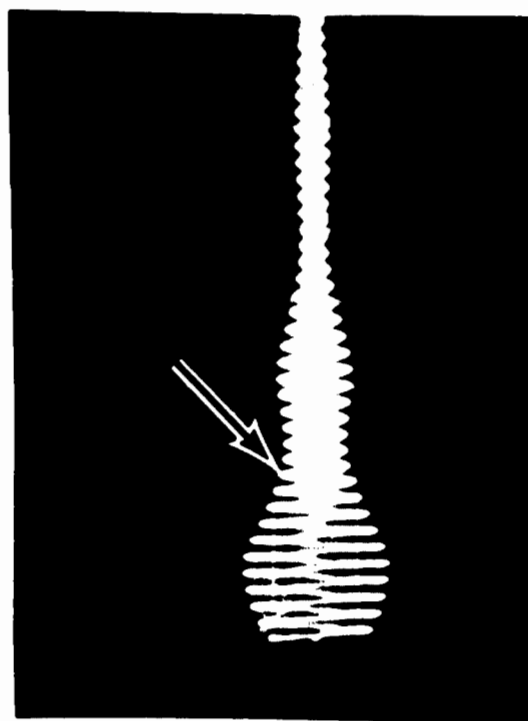
CELL CENTER



WATER CONDITION



CELL WALL



DEBOND CONDITION

Figure 6 OSCILLOSCOPE DISPLAY OF EDDY SONICS OUTPUT SIGNAL FOR HONEYCOMB CORE PANELS

However, by comparing the envelopes of the RF presentation from the debond with that from a bond over the cell wall, the length of the envelope is observed to increase. As shown, a greater number of peaks in the envelope are observed to exceed an arbitrary amplitude threshold assigned to the good bond. In addition, by placement of the probe over an area of the sample which contains water in contact with the facing sheet, a third distinct RF display is observed. In this case, the amplitude of the envelope, as well as the length, has diminished. Thus, by using the Frequency Counting Eddy Sonics approach, simultaneous debond and water detection is possible. This would not be possible using amplitude detection only.

5.3 Low Frequency Pitch-Catch Ultrasonics

The Low Frequency Pitch-Catch Ultrasonics technique provides a couplant-free nondestructive technique for detection of debonds in non-metallic panels. The developed technique uses commercially available low frequency pulsed ultrasound instrumentation (Automation Industries Sondicator) as shown in Figure 7.

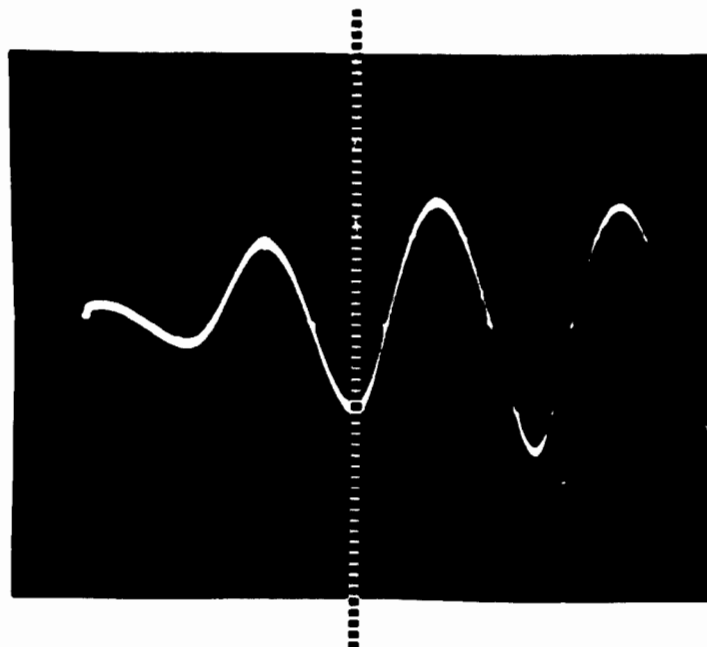
The scanning probe contains two piezoelectric crystals (combined into a single hand-held housing), one of which transmits low frequency (25 kHz) sound into the material with the second crystal acting as a receiver. The shelter inspection results are determined by an analysis of the combination of the amplitude and phase of the reflected energy sensed by the receiver. These variations are displayed on meters.

An example of bond and debond in the resin-impregnated honeycomb panel with fiberglass face sheet is shown in Figure 8. Figure 8a is the received signal from a bonded area, and Figure 8b shows the change in amplitude (y-axis variation) resulted from a debond area to be small. However, there is about a 180° phase shift (x-axis variation). This shift can easily be monitored on a meter and reliably detects debonds in fiberglass/honeycomb panels. Debonds of approximately 1" in diameter have been detected in fiberglass-to-honeycomb panels by this phase technique. Monitoring the amplitude meter provides the operator with coupling adequacy information.

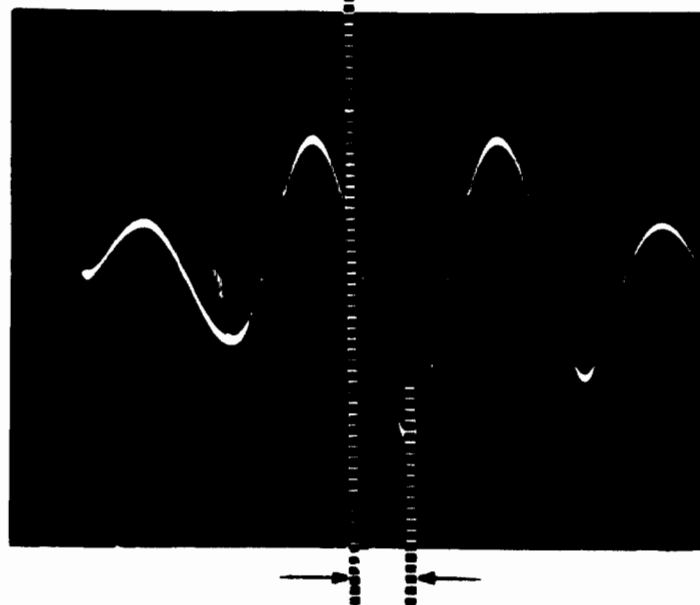
Although neither fiberglass-to-balsawood nor fiberglass-to-foam panels were available for this laboratory evaluation, the inspection principle remains valid for these panel types. It is therefore reasonable to assume that the



Figure 7 LOW FREQUENCY PITCH-CATCH ULTRASONIC INSPECTION INSTRUMENTATION



(a) BOND CONDITION



(b) DEBOND CONDITION

Figure 8 RF DISPLAY OF RECEIVED SIGNALS FROM LOW FREQUENCY PITCH CATCH ULTRASONICS INSPECTION OF FIBERGLASS-TO-HONEYCOMB PANEL

inspection technique will apply with equal reliability for the detection of both debond and water in these panel configurations.

5.4 High Frequency Pitch-Catch Ultrasonics

The High Frequency Pitch-Catch Ultrasonics technique can provide a non-destructive single-cell sampling inspection method for detection of water in honeycomb cored material panels with both metallic and non-metallic facing sheets. The technique involves introducing pulses of ultrasonic energy into the test part and detecting the reflection of the ultrasonic energy from the water to adhesive interfaces in full cells or water to air interface in partially full cells, if the geometry is appropriate.

The developed technique uses basic ultrasonic thickness gaging instrumentation. Operation of a standard ultrasonic thickness gage is relatively straight forward in a shelter inspection application. An ultrasonic pulse is transmitted into the material to be measured. At the same time, a clock circuit is actuated and a blanking pulse is generated to shunt the receiver to prevent overloading. At the end of the blanking pulse interval, the receiver circuit is actuated and the first reflected pulse then received stops the clock. The pulse transit time measured by the clock provides a measurement of the material thickness. The oscilloscope presentation of the signal resulting from transducer placement over a dry honeycomb cell using the standard gage is shown in Figure 9. The lengths of time of the blanking pulse and the reflected signal, from the adhesive-to-air interface at the near side facing sheet, which stops the clock circuit are shown. The measurement provided by this signal indicates the thickness of the adhesive-backed front face sheet. When water fills a honeycomb cell, the resulting reflection from the water-adhesive interface actually appears later in time than the front face sheet-adhesive reflection. (See Figure 10.) Standard instrumentation, however, is not capable of detecting the above second (water-adhesive interface) reflection in a single measurement, since the clock circuit has already been stopped by detection of the earlier reflection from the interface at the front surface.

To extend the capability of the available instrumentation to provide the desired water path length measurement for honeycomb cell inspection, in-house modifications were made which consisted of changes to the internal clock circuit and reduction of the instrument operating frequency. The

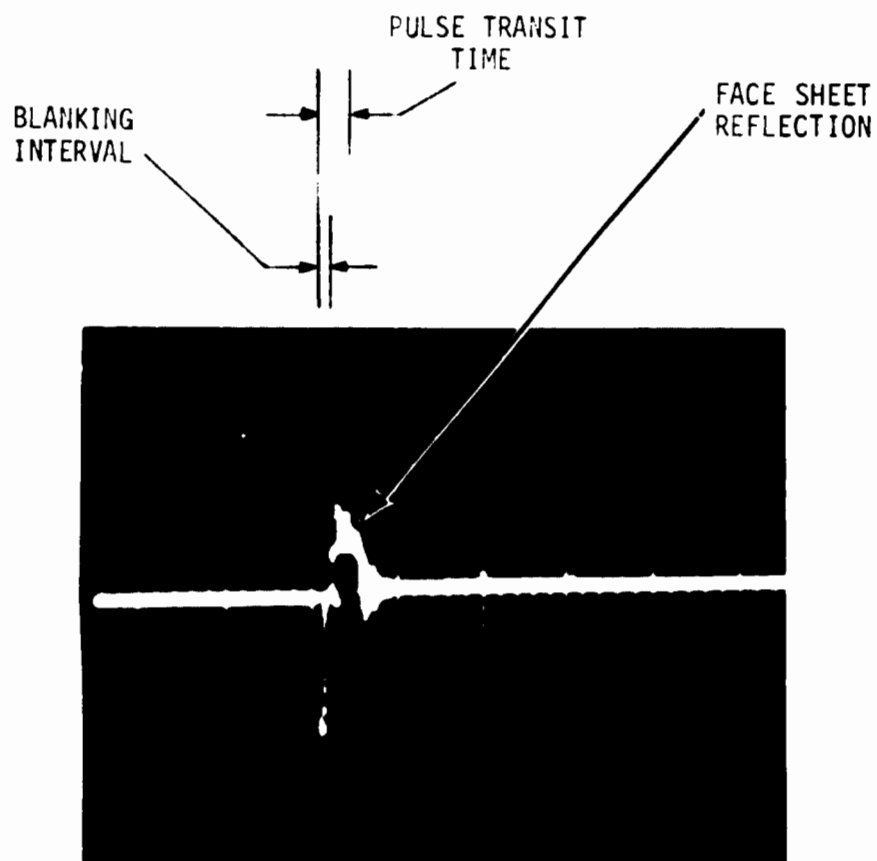


Figure 9 STANDARD ULTRASONIC THICKNESS GAGE OSCILLOSCOPE
DISPLAY FOR DRY HONEYCOMB CELL

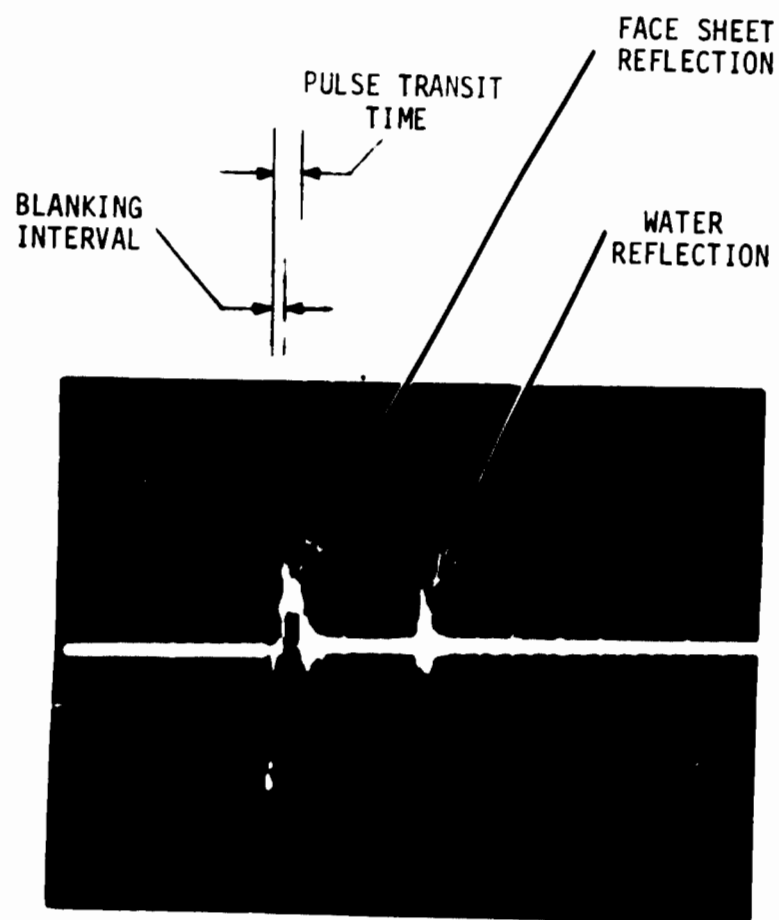


Figure 10 STANDARD ULTRASONIC THICKNESS GAGE OSCILLOSCOPE
DISPLAY FROM HONEYCOMB CELL CONTAINING WATER

clock circuit was changed by introduction of a modified blanking circuit which extended the blanking interval, thereby enabling the receiver circuit to ignore the first reflected signal which results from any front sheet interface. (See Figure 11.) By ignoring this reflected signal, the receiver detects the next reflected pulse which is provided by the water-to-adhesive interface, as shown in Figure 12, if water is present. This signal now provides the "first" reflected signal which stops the clock. Using the velocity of sound in water and the time measured by the clock, the water thickness can be determined. Laboratory tests conducted with the modified instrumentation have demonstrated reliable detection of an approximate minimum of 3/8" of water thickness in a 1/4" diameter cell by this technique.

To further enhance the technique for the current inspection requirements, the operating frequency of GARD's thickness gauge was lowered to 2.25 MHz from the standard 5.0 MHz for the demonstration work by appropriate selection of ultrasonic transducers and preamplification of the reflected acoustic pulse. The final version of the inspection instrumentation is planned to operate at 1 MHz to reduce the effects of the high attenuation characteristics of the nonmetallic panel composites and thus further improve signal-to-noise.

5.5 Field Evaluation of Applicable Techniques

The three above described shelter panel inspection techniques were tested on Bare Base shelters of the 4449th Mobility Support Squadron, Holloman Air Force Base. The inspection equipment arrangement used in this field evaluation is shown in Figure 13. With the help of 4449th personnel, twenty-five shelters were inspected with a variety of structure compositions (aluminum-to-foam, aluminum-to-honeycomb, and fiberglass-to-honeycomb) having a range of face sheet thicknesses. These shelters were inspected and areas which gave defect indications were marked. The standards used for equipment calibration were the natural occurring debonds in the panels used for the preliminary laboratory investigation at GARD. The shelters were then inspected with a standard coin tap test for debonds and with destructive tests for water to verify the results.

5.5.1 Frequency Counting Eddy Sonics

The first set of shelters inspected were expandable shelter containers (ESC) having aluminum face sheet and foam core. The fifteen shelters which were tested included a number of production models. The second set

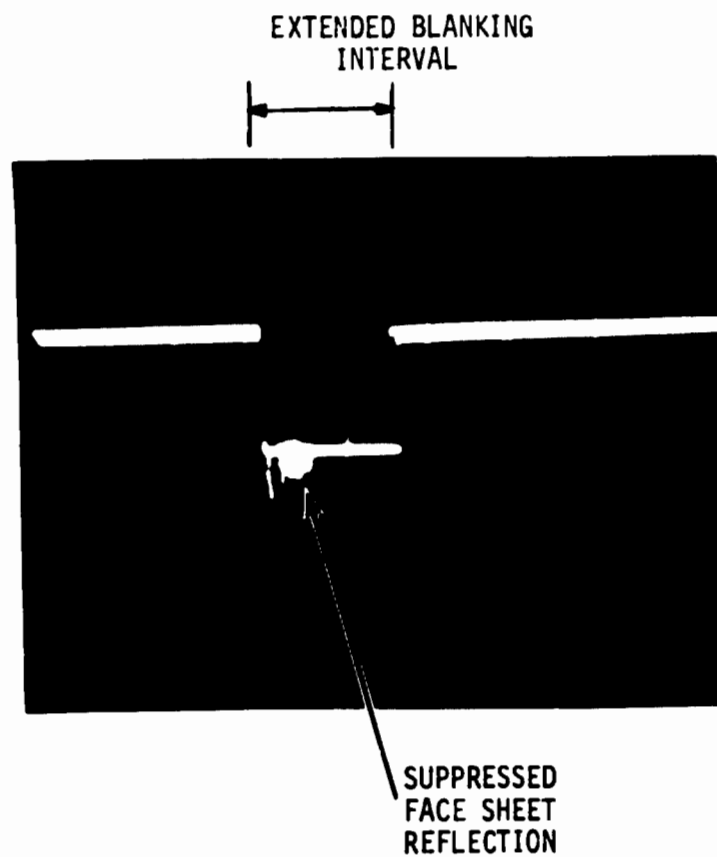


Figure 11 OSCILLOSCOPE DISPLAY OF ULTRASONIC THICKNESS
GAGE MODIFIED TO ENTEND THE BLANKING INTERVAL

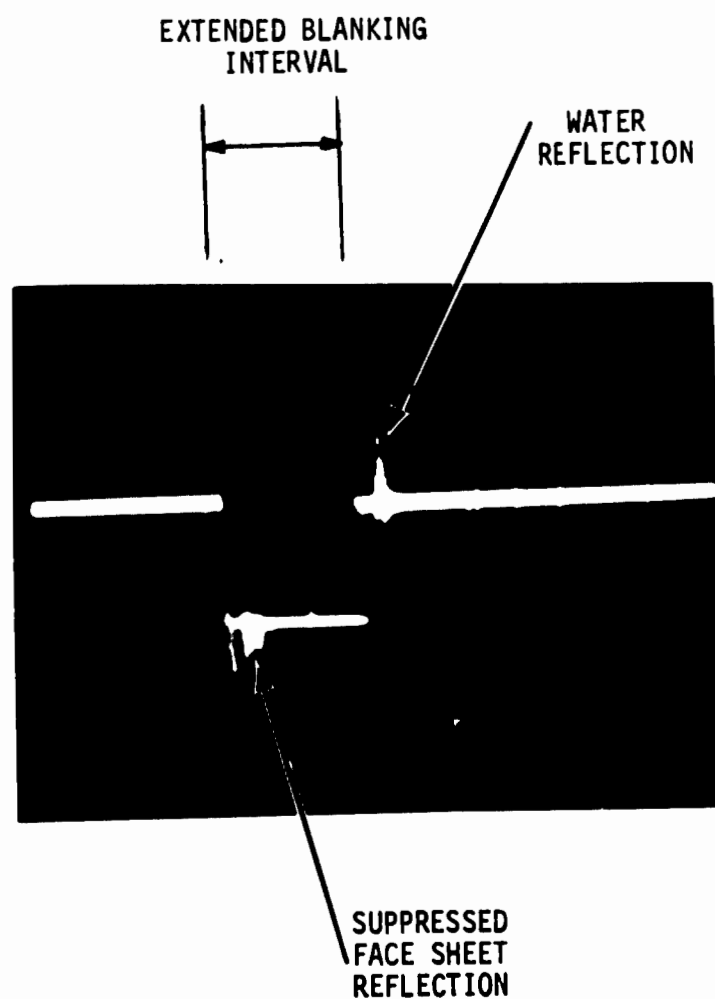


Figure 12 OSCILLOSCOPE DISPLAY OF MODIFIED ULTRASONIC THICKNESS GAGE USED TO DETECT WATER



Figure 13 INSPECTION EQUIPMENT AS USED IN FIELD EVALUATION

of shelters tested were expandable personnel (EXP) shelters with aluminum face sheet-resin impregnated paper honeycomb core panels. The ten shelters which were inspected again included a number of production models. The modified eddy sonics system reliably detected 2" diameter debonds in both types of shelters. The effects of face sheet thickness variation on debond detection were examined by inspecting the walls, floors, and doors of the shelters. The range of face sheet thicknesses were from 0.020" to 0.045" thick. The system detected 2" debonds in all panels tested in each configuration without any adjustment of the equipment controls. However, it should be noted that equipment adjustment must be performed when changing the inspection from foam core to honeycomb core panels. Instrument gain adjustments are also necessary for inspecting panels with vinyl or epoxy paint coatings. Such coatings vary in thickness from normal paint and, thereby, change the probe to face sheet spacing. This situation is normal in electromagnetic testing and this inspection system provides compensation by electronic gain adjustment.

The Frequency Counting Eddy Sonic System did not show any significant change in test readings when the probe was passed near the edge of a panel. Edge effects could be noticed only when the detector was placed over the edge of the test specimen. The system was sensitive to the surface condition of the panel under inspection. Dents, foreign material, or severe contour changes cause change in instrument readings and yield false indications. However, this ambiguity is not considered detrimental to the ultimate application of this inspection method. Based on past experience, in the majority of cases, a debond will be present in these areas.

The presence of water in two foam core and two honeycomb core shelters was detected during actual inspection. Three water indications were located at panel edges. Water presence was verified by physically exerting pressure on the panel edge with resultant water seepage. The fourth indication (a single cell) was verified by piercing the face sheet and again water seepage occurred.

5.5.2 Low Frequency Pitch-Catch Ultrasonics

Low Frequency Pitch-Catch Ultrasonics was used to inspect several fiberglass face sheet and paper honeycomb core panels. These panels were inside new EXP shelters. The inspection of this type of panel

necessitated the opening of the shelter (a lengthy process). Therefore, only a small number of such panels were inspected during this field evaluation. The panels were completely inspected with the Sondicator and no debonds were found; visual and coin tap inspections showed no debonds were present.

5.5.3 High Frequency Pitch-Catch Ultrasonics

The High Frequency Pitch-Catch Ultrasonic water detection technique is applied to the inspection of fiberglass-honeycomb panels. As already discussed in the preceding section, the fiberglass-honeycomb panels inspected were relatively new and in good condition. Due to the overall good condition of the panels, no debonds were detected. This technique was used to verify the presence of water detected with the Frequency Counting Eddy Sonics inspection on two metal-to-honeycomb panels. The presence of water in both panels was easily detected and verified as previously described.

These results, in conjunction with the consistent results obtained in the laboratory (on fiberglass-paper honeycomb), indicate the High Frequency Pitch-Catch Ultrasonic technique will provide the necessary water detection capability for these panels.

5.6 Discussion of Field Results

The selected NDT techniques were field-tested on approximately 25 shelters. The Frequency Counting Eddy Sonic system demonstrated the capability for reliable detection of both debond and water defect conditions in panels with metallic face sheets. This system detected 2" debonds at an inspection rate of approximately 600 square feet per hour.

Inspection of fiberglass-to-paper honeycomb panels for debond was accomplished using the Low Frequency Pitch-Catch Ultrasonic technique. The panels inspected were relatively new and in good condition, and no debonds were detected. Due to the overall good condition of the panels, no water detection procedure was required on these panels in the field. However, consistent results obtained in the laboratory indicates the reliability of a sampling procedure using a High Frequency Pitch-Catch Ultrasonic technique which can provide the necessary inspection capability for these panels. The High Frequency Ultrasonic technique successfully demonstrated the capability for detection of water in single cells of metal-to-resin-impregnated paper honeycomb panels.

Each of the NDT techniques selected for field evaluation met, or exceeded, the inspection requirements for detection of debond and water defect conditions in shelter panels.

Following the field evaluation, a technical conference and inspection technique demonstration was held for the purpose of informing other agencies about the work performed under this program. The conference consisted of:

- a) A presentation of a review of the program objectives, GARD's approach to the problem, current status of the program, and future plans.
- b) A demonstration of the actual inspection system in operation,
- c) An open discussion to assess the capability of the inspection techniques in terms of present shelter inspection requirements.

The briefing and demonstration was well received by all the attendees. The conference was extremely worthwhile in terms of exchange of ideas and inputs from the various government agencies.

Based upon the favorable results obtained during the first field test, together with favorable Air Force maintenance personnel acceptance, approval was given by the Air Force project monitor to proceed with Phase II of the program.

5.7 Phase II: Prototype Fabrication and Field Test

In Phase II, a prototype system, based upon the successful work in Phase I, was designed, fabricated, and field tested. Inspection procedures for equipment field use were developed, and an operating manual was written.

The inspection equipment was field evaluated on Bare Base shelters of the 4449th Mobility Support Squadron at Holloman AFB. The objective of this evaluation was to verify the equipment inspection capabilities, reproducibility and accuracy in a field environment. Also to provide training of Air Force candidate operating personnel. Figure 14 shows the prototype equipment in operation at Holloman AFB.

The inspection equipment was field-tested on about 30 shelters. The Frequency Counting Eddy Sonics System demonstrated the capability for reliable detection of both debond and water defect conditions in panels having metallic face sheets. The system detected 2" debonds at an inspection rate of about 600 square feet per hour. Debonds smaller than 2" can be detected with slower scanning rates.

Inspection of fiberglass panels was not accomplished since it required opening of the shelters to gain access to them and time or personnel were not available for this phase of the test. However, consistent results obtained in the laboratory and previous field tests indicates the reliability of the Low Frequency Ultrasonic Pitch-Catch Technique can provide the necessary inspection capability for these panels. The High Frequency Ultrasonic Technique successfully demonstrated the capability for detection of water in single cells of metal-to-resin impregnated paper honeycomb panels.

An interesting comparison was made between the prototype inspection equipment and the conventional "tapping" method for detecting debonds. Several shelters were randomly selected for inspection, including both foam-and-beam and honeycomb shelter types. An experienced "tapper," using a standard aluminum tap

hammer, then inspected each shelter carefully, marking the apparent debond areas with chalk. Then, the prototype NDI equipment was used to inspect each shelter, again marking the debond areas with chalk. The two methods could thus be easily compared. On foam-and-beam shelters, it was observed that the tapping method was fairly reliable, detecting each of the debond areas - although the NDI equipment generally indicated debonds approximately 2 to 6 inches beyond the "tapped" chalk areas. On honeycomb shelters the tapping method was very unreliable. Figure 15 shows the results on one honeycomb shelter. When the shelter was tapped, only the bottom right hand corner, shown by the dashed lines, indicated a debond area. When the shelter was inspected with the NDI equipment, approximately 20 other debond areas were detected, shown by the solid lines in the photo.

Following the equipment evaluation, training of Air Force operating personnel was accomplished. The training consisted of:

- a) A presentation of program objective, GARD's approach to the problem and current status of the program.
- b) A demonstration of the actual inspection system in operation.
- c) Two days of equipment set up and inspection of shelters with a variety of structure compositions having a range of face sheet thicknesses.

Each of the NDT techniques met, or exceeded, the inspection requirements for detection of debond and water defect conditions in shelter panels.

The field evaluation provided valuable input for future improvements to the operational characteristics, size and weight of production models. Better control of coil wave form is required and finer control over oscillator output voltage is also needed. To obtain these desired goals tight specifications on purchased components need to be written.

Several field inspections have been performed. The results and the modifications to the original equipment have produced an operational, field ready, system configuration. However, the system is bulky and heavy (about 30" X 21" X 29" and 200 lbs. with batteries; 120 lbs. without batteries). It is recommended that future units undergo miniaturization to reduce both size, weight and improved operational characteristics. Depending upon the number of production units required, a miniaturization program could be cost effective. It is estimated that the weight and bulk can be reduced to 1/4 its present size.

In production, it is estimated that the eddy sonic system would cost \$17,000 each, assuming a production quantity of 50 units. It is estimated that the miniaturized version would cost \$10,000 each for the same quantity. These estimated costs are based on 1975 prices.



Figure 14 INSPECTION OF SHELTER WITH PROTOTYPE EQUIPMENT

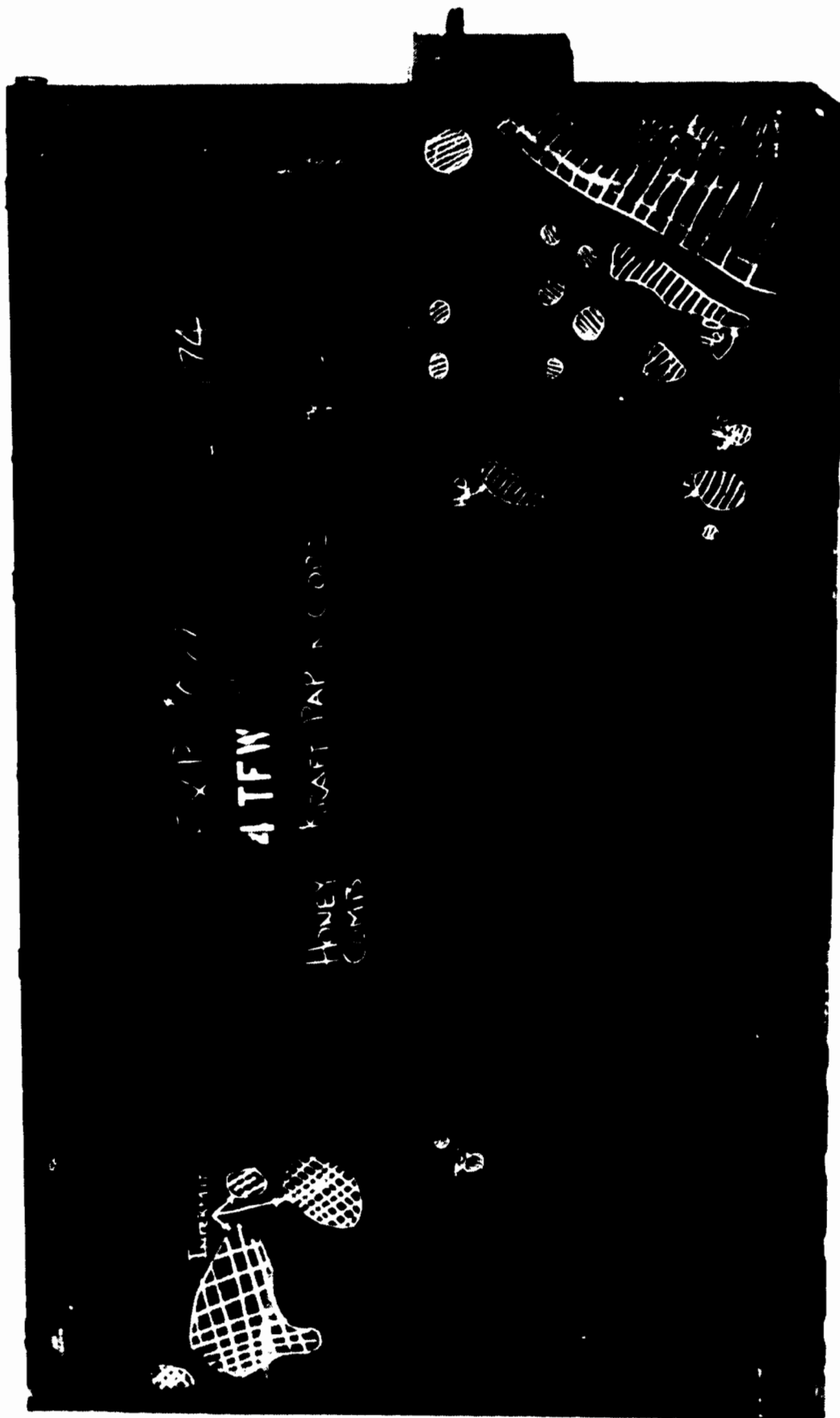


Figure 15 TYPICAL INSPECTED SHELTER

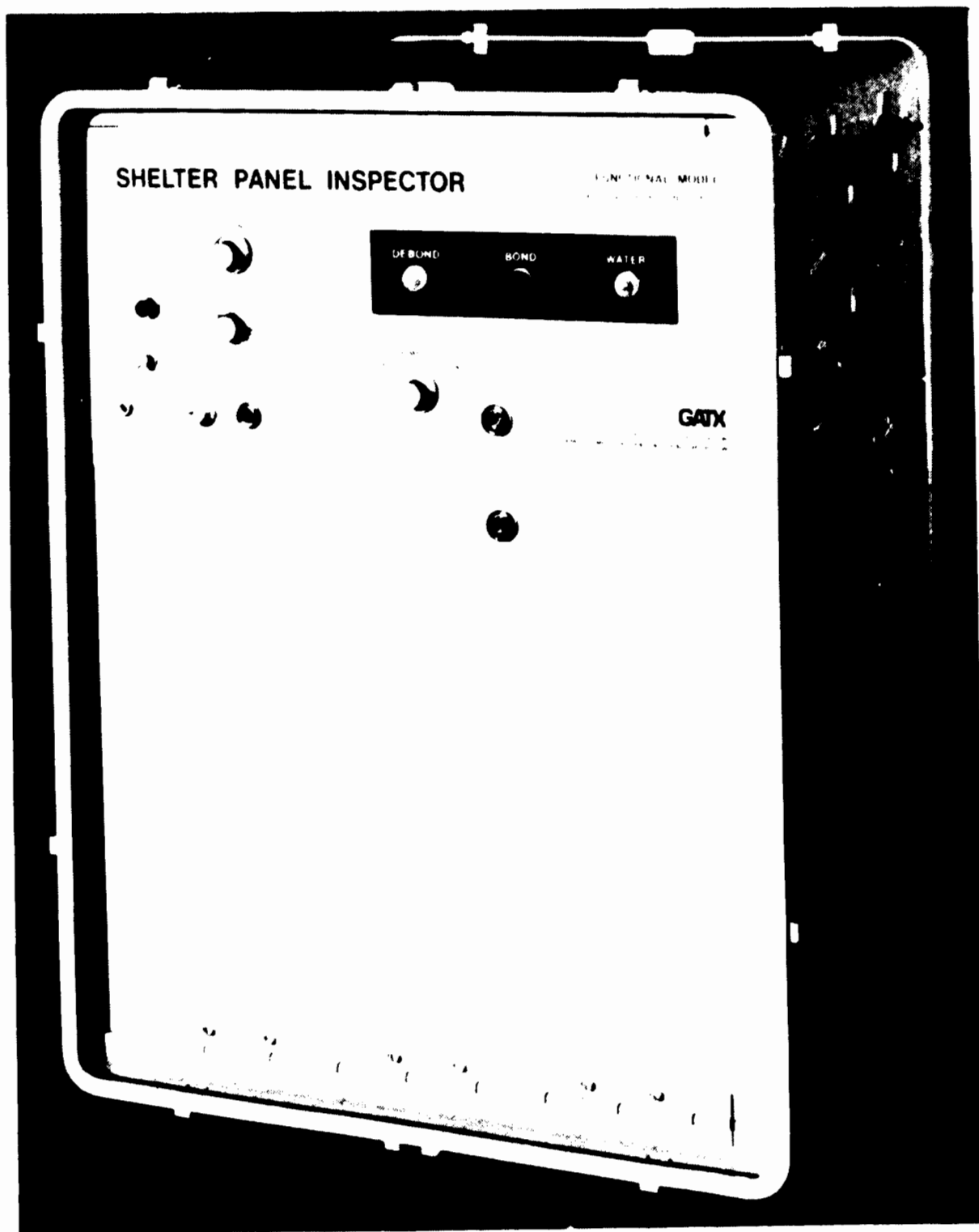


Figure 16 PROTOTYPE EQUIPMENT

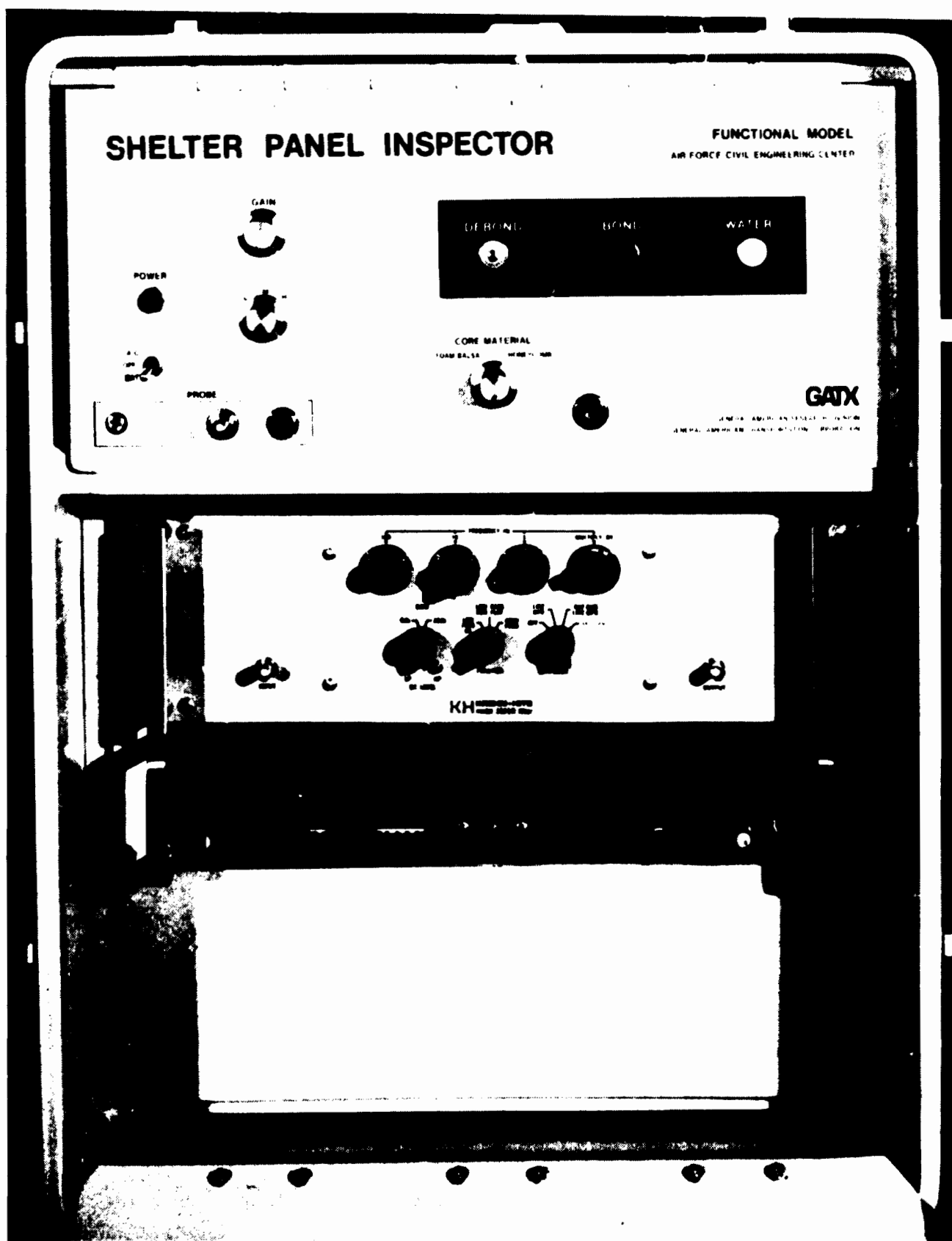


Figure 17 PROTOTYPE EQUIPMENT WITH
FRONT PANEL DOWN

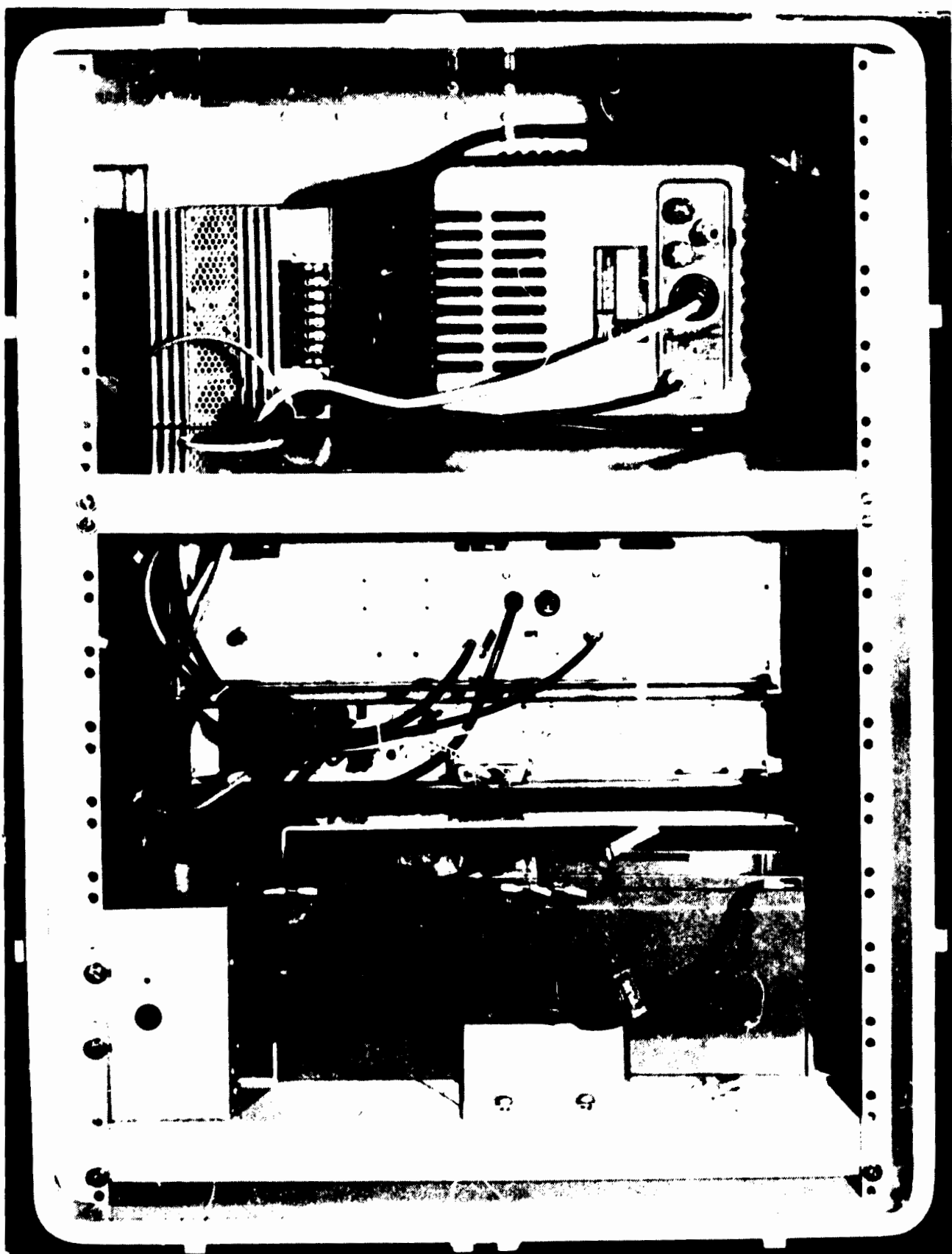


Figure 18 PROTOTYPE EQUIPMENT/REAR PANEL REMOVED

APPENDIX A
QUALITATIVE NDI EVALUATION

- . Debond Detection
- . Moisture Detection

DEBOND DETECTION

This part of Appendix A is a qualitative evaluation of the applicability of general nondestructive inspection methods to debond detection in shelter sandwich panels. The methods are discussed according to the type of energy used: Electromagnetic/Electronic, Mechanical, Optical/Infrared, Penetrating Radiation, and Ultrasonic/Sonic. During the evaluation we eliminated those methods which are inapplicable to the problem. Those remaining are broken down into constituent techniques which, in turn, are considered for practicality in terms of the stated problem: They have to find a 2" diameter debond, in a scanning mode, in a field environment. The chosen technique(s) should be single sided and state-of-the-art proven for outdoor field applications.

Electromagnetic/Electronic Techniques

The use of these requires that the presence or formation of a debond alter the electrical or magnetic characteristics of the panel. Part of the material inspected must therefore be electrically conductive or magnetically permeable. Since 90% of the facing sheet material is aluminum, methods sensing variation of electrical conductivity can be considered. However, no core material (phenolic coated cardboard, foam, balsa) is electrically conductive or magnetically permeable, so a debond between the core and facing sheet would not change the electrical properties of the panel to any practical extent. Therefore, techniques utilizing electromagnetic or electronic dependent approaches are not, as a class, inherently applicable for detecting sandwich panel debonds.

There is, however, a hybrid technique which senses vibration generated by electromagnetically induced eddy currents in inspected materials. The technique is called Eddy Sonics. With it, debonds alter the intensity and frequency of resonance of a normal panel. The vibration is generated by an imposed electric field which is coupled directly to a metallic facing sheet. The method does not require couplant. Thus, it may provide a quick, field scanning inspection. Eddy Sonics was, therefore, selected for laboratory evaluation.

Mechanical Techniques

The use of these methods requires that the presence or formation of a debond alter the mechanical characteristics of the panel. Material of any composition can be inspected. There are a large variety of techniques which might be considered for this application. Ultrasonic/Sonic techniques are in actuality "Mechanical" techniques. However, in this report they are considered separately and will be discussed later.

The Brittle Coating technique relies upon localized fracture of a stress-sensitive brittle film which is applied in a liquid form to the test surface and allowed to dry. When dry, the film responds to stressing of the test surface beneath it by mechanical fracture of the coating. Strain Gaging is another coating technique which directly measures mechanical properties of a test sample. This technique also necessitates application of a controlled stress to the sample. Acoustic Emission is capable of detecting "noises" related to defect formation in materials. But it, like the two preceding techniques, requires application of a controlled external stress on the work piece to generate the associated defect response. Such controlled stressing on large (8' x 10') panels is considered impractical for this project. Hence, these techniques are not considered applicable.

A Vacuum Test can detect debond presence by using vacuum suction to apply a local stress normal to the surface of the inspected material. In region of debond, this induces a sheet deformation greater than that induced in intact regions because an area with lack of bond creates less resistance than an area of good bond to the tensile pull generated by the vacuum. Such deformation is typically measured by a displacement transducer. The method holds promise for detecting debonds throughout panel depth, requires minimal physical contact, and is relatively immune to ambient conditions. If a good scanning rate and adequate sensitivity are possible, this would be an attractive inspection. Sensitivity may be a problem since a theoretical 14.7 psi limit exists on pull. Practical limits are probably much lower. Since a commercial piece of equipment exists which uses this principle, it was laboratory analyzed.

Optical/Infrared Techniques

The use of these requires that the presence or formation of a debond alter the Infrared, or thermal, characteristics of the shelter panel, or

the sensing part of an Optical interrogation system. These techniques, as a class, are dependent upon the same type of debond-induced changes as Mechanical techniques. However, Optical/Infrared techniques typically use "light" to transfer information about the debond indication -- whereas, Mechanical techniques use physical contact for this transfer.

Optical techniques applicable here depend upon the measurement of displacement. Since panel surface displacements are generally small (for small disbonds) a sensitive technique is required. Holography is such a technique. It uses interference patterns of coherent light from stressed vs. non-stressed panels, or time averaged vibration, to generate debond information. This technique has proven reliable for use in the detection of laminate debonds under controlled laboratory or indoor production conditions. Field use for debond detection in shelter panels poses significant problems. First, for outdoor use, the technique is only at the feasibility stage. Slow inspection speed and lack of instant readout are further disadvantages. The first difficulty alone (lack of currently applicable, field proven hardware) makes the technique inapplicable based upon the Problem Definition outlined in the report proper. No other Optical debond detection technique is as advanced developmentally as holography. Thus, Optical techniques were not considered further in this program.

The use of Infrared, or Thermal, techniques requires that the presence or formation of a disbond alter the thermal coupling or heat conductive pathways of the panel. Material of any type can be inspected, though materials of low specific heat require greater sensitivity in detection instrumentation. "Passive" sensing will not work in this application because ambient conditions will normalize any potential gradient effects. An "active" inspection system is required. Some sort of "hot spot" scan or detection has to be implemented to utilize the thermal gradients needed for the method to work since a one-sided inspection is needed. A source/detection scanner is not commercially available and would have to be built.

Standard Thermography (i.e., IR cameras) could be used for detection if sufficiently powerful heat source was available. However, regardless of sensitivity, the uncontrollable variation of color and temperature levels in the panel due to impinging solar radiation, makes calibration of any instrumentation

difficult even in the hands of highly-skilled operators. Liquid crystals or thermal phosphors as readout means will not help to overcome the lack of a heat injecting scanner. Therefore, the Infrared/Thermal techniques, as a class, are not considered feasible for this application.

Penetrating Radiation Techniques

The use of these requires that the presence or formation of a debond alter the effective density of the panel exposed to penetrating radiation (i.e., neutrons or X-rays, since beta or alpha particles would not be strong enough to sense the changes which would be present) in either a backscatter or transmission mode. Since an ordinary debond does not add to the radiation modulation of a material, the use of penetrating radiation to detect such panel debonds is not inherently feasible.

Debonds associated with crushed core, voids in the adhesive, or missing core will be detectable by their secondary effects (i.e., resulting localized density changes). However, such defects are in the minority of defects to be detected. Further, the logistic problem generated by 100% inspection of large panels by radiation techniques makes the approach undesirable.

Thus, these techniques are considered inappropriate for the debond detection application. However, the most common permutation of this method (thru-transmission X-Radiography) is highly sensitive and can provide images of the above described detection-amenable defects. Therefore, X-Radiography can be used as a standard, since operators can easily relate to the resulting pictures when calibrating other inspection techniques.

Ultrasonic/Sonic Techniques

The use of these techniques requires that the presence or formation of a debond alter the acoustic properties of the panel. Material of any composition can be inspected. In standard inspection configurations, intensity/time variations of acoustic energy are used as detection indexes. The ease of mechanical coupling to the material to be inspected, and the poor acoustic coupling between air and the material at the frequencies used, make these methods relatively insensitive to ambient interference and potentially applicable for detecting shelter panel debonds. There are many differing implementations of these techniques using phase, amplitude, and time for detection. They are discussed below as they relate to the problem at hand.

Thru Transmission can measure the attenuation of sound energy as it passes through the inspected material and interacts with the free surfaces of debonds. The attenuation change can be a measure of debond presence. This technique is inherently a highly sensitive detector of debonds. However, the difficulty of properly aligning two transducers, one on each side of a given panel, and the established requirement of one-sided inspection, makes this approach undesirable.

Pitch-Catch uses the same principle as Thru Transmission, but places both transducers on the same side of the material, eliminating the two-sided objection posed against the latter method. Both high frequency and low frequency versions of this technique are available. However, high frequency ultrasonics is subject to a limitation imposed by the necessity of applying a liquid couplant between each transducer and the material inspected. This couplant need renders a variety of other high frequency methods, including Lamb Wave and Pulse Echo inspections, impractical for the detection of sandwich panel debonds in this application because, as described in the Problem Definition, couplant complicates the inspection process, and in a hand scanning scheme, makes it intrinsically slower.

Resonance measures the change in vibrational resonance of the inspected material due to debond presence. While such a measurement can be made with the sample subjected to continuous or pulsed excitation, standard NDI nomenclature identifies Resonance inspection as that performed with continuous excitation. This method uses probe loading effects to identify the presence or absence of a debond. While standing wave effects do occur, and usually make data interpretation difficult, there is a readily available, standard debond detection tool based on this technique. It was evaluated in the laboratory phase of this program.

Pulsed Acoustic inspections can be made with either mechanical impacters (Acoustic Impact inspection) or piezo-electric drivers (Point Contact Sonics). Resulting vibrations are usually sensed piezo-electrically. The latter technique can also be called Low Frequency Pitch-Catch Ultrasonics. Work with the former has been mostly limited to the R & D area; the latter has commercially available instrumentation based on it. Since the former is easy to implement, neither require liquid coupling, both have demonstrated previous success in debond detection, both should be laboratory tried for this application.

Summarizing the above, qualitative discussions have determined that nondestructive inspection techniques which should be considered for detection of shelter sandwich panel debonds are: Eddy Sonics, Vacuum Testing, Resonance, Acoustic Impact, and Low Frequency Pitch-Catch Ultrasonics. The major reasons for these selections are their absence of liquid coupling, equipment availability, simplicity of use, and general independence of materials being tested.

A table listing these by category is presented at the end of Appendix A, after the discussion on Moisture Detection which follows.

MOISTURE DETECTION

This part of Appendix A is a qualitative evaluation of the applicability of nondestructive inspection methods to the detection of moisture in shelter sandwich panels. Here, like in the preceding section on debond detection methods, we first consider the applicability of general methods (as previously categorized) and then discuss specific techniques of methods determined to be potentially applicable. It is understood that the stated moisture detection problem has been refined to that of spot moisture detection in previously identified debonds. This was established in the Problem Definition section of the report proper. In the case of foam or balsa cores, water present in debonds will take the form of a thin film. An arbitrary detectability threshold of 0.020" of water has been selected for this film. With a honeycomb core, a thermal short (i.e., water contact between facing sheets), one cell in volume, was established as the desired detection threshold.

Electromagnetic/Electronic Techniques

As previously explained in the Debond analyses, these methods require part of the inspected material to be electrically conductive and/or magnetically permeable. Water satisfies the condition of electrical conductivity, thus making this an attractive group of techniques to consider.

The desirability of single sided inspection and the preponderance of metal facing sheets makes the standard electric moisture detection approaches of Resistivity or Dielectric Constant measurement inapplicable. Microwave measurements through a metal facing sheet to detect water would be unrealistic. The Eddy Sonics technique described previously may be applicable if the presence of water will sufficiently affect the resonance properties of the facing sheet to allow its detection. Eddy Sonics was chosen for laboratory investigation.

Mechanical Techniques

The relative incompressibility of water compared to that of air might be exploited to differentiate debonds containing water from those without water. Debond regions with little or no water present would yield strain proportional to the stress applied. Regions filled, or nearly filled, with water might yield less strain for a given stress, since the water is partially constrained by debond edges.

Implementation of an inspection method based upon this phenomenon would require external stresses as described in the Debond Section of this Appendix. Brittle Coatings, Strain Gaging, and Acoustic Emission are all, therefore, impractical. Vacuum Testing while potentially useable for debond detection would be less likely to find water. However, since a Vacuum Testing system will be examined for debonds, it will also be laboratory evaluated for water detection.

Optical/Infrared Techniques

In considering the applicability of Optical techniques to water detection, the Debond section observations apply. It is still necessary to locate a subsurface anomaly by viewing its resultant surface effect. Again, Holography has detection potential. However, its sensitivity for water detection will be less than for debond detection. And we have already eliminated Holography for inspection constraints which likewise apply here. Thus it, and any other Optical techniques, are considered impractical here also.

Infrared techniques can exploit differences of specific heat capacity and thermal conductivity between air and water for water detection in debonds. Unfortunately, the facing sheet has thermal properties, and to a first order of magnitude it will mask thermal water effects. In addition to this, the technique still would have to overcome the great environmental temperature extremes. Also, some type of scanning or pulsing system would have to be developed to generate the thermal gradients needed for detection. This development by Problem Definition is undesirable. As with debond detection, Infrared techniques are considered impractical for this application.

Penetrating Radiation Techniques

These techniques exploit penetration, scattering, and absorption cross-sectional differences between water and air. They have been used

successfully in the past for water detection. They have the advantage of high resolution and, in some cases, imaging of the inspected area. Their consideration for water detection is much more valid than for debond detection because for water detection only local inspection (in a predetermined, debonded area) is required. Even the fact that standard X-ray inspection is a two-sided test is not as detrimental as in debond inspection, where 100% sample coverage is required.

Potentially applicable penetrating radiation techniques are X-ray Backscatter and Transmission and Neutron Backscatter. The added density of water provides the detection mechanism for X-rays, and the presence of the hydrogen atom in water provides the detection mechanism for neutrons.

X-ray water detection is currently being used in sandwich panels by the Air Force and has been used for water detection in honeycomb tiles, rubber tires, etc. The technique thus deserves evaluation in terms of sensitivity and ease of use, however, equipment bulk, processing requirements, and associated health precautions make it undesirable for this application except as a last resort. Paper and film radiography are both candidates for use. The former is not as sensitive as the latter. However, from a development time and a cost point of view, the paper process is much more desirable. Laboratory tests are required to determine whether the paper process can be adequate for the needs of this program.

The above comments apply to both X-ray Transmission and Backscatter. Backscatter is much more desirable since it is a one-sided inspection. However, it has the disadvantage of requiring a high voltage source (150 kV vs 50 kV for thru-transmission).

The comments which apply to X-ray Backscatter also apply to Neutron Backscatter. The latter is a standard inspection used for water detection in soil. Field hardened equipment using counter detection is available. However, the sources used are high in output since they have to penetrate deep into the soil (i.e., 6-8 inches). Modification to the source is expected to be needed to allow for water film detection in a panel. Sensitivity determination of the neutron approach in this application must await laboratory investigation.

Ultrasonic/Sonic Techniques

These techniques will depend upon the differences in acoustic interaction between facing sheet and air, and facing sheet and water, to detect the

presence of water in a debond. Although Ultrasonic/Sonic Techniques are essentially impractical for rapid scanning rates because of necessary liquid acoustic couplants, they are, nevertheless, candidates for evaluation for use as back-up inspection techniques.

Thru-Transmission is still undesirable since it is a two-sided inspection. Pulse Echo, High Frequency Pitch-Catch, and Low Frequency Pitch-Catch Ultrasonics are all potentially useable and could be tried in the laboratory in order to determine applicability. It is expected that these techniques may not work reliably in foam or balsa core applications, where thin film water detection behind thin facing sheets is the problem. In this case, internal surface irregularities, due to the debonded adhesive, may create background noise signals making water detection difficult. With honeycomb core, the presence of water in amounts equal to the established threshold limits should allow signal reflections off the back surface of the panel and thereby generate a favorable Pulse Echo or Pitch-Catch inspection.

Pitch-Catch and Pulse Echo Ultrasonic techniques can both identify the back surface of a honeycombed shelter panel. The former uses two transducers, the latter uses one transducer. The one transducer Pulse Echo technique can be subject to ringing problems and is more difficult to use for an ultrasonic gauging system. Since GARD available gauging equipment operates by Pitch-Catch, the laboratory investigation was limited to Pitch-Catch.

Resonance, either continuous wave or impact (as discussed in the Debond Detection section) is also potentially useable for water detection since the presence of water should result in changes in the vibration characteristics of the panel being inspected. The Resonance equipment, the Acoustic Impact approach, and Low Frequency Pitch-Catch Ultrasonic techniques, all discussed previously, were selected for laboratory investigation.

Summarizing, potentially applicable inspection techniques for water detection in shelter panels, based upon the preceeding evaluations are: Eddy Sonics, X-ray Thru Transmission and Backscatter, Neutron Backscatter, High Frequency Ultrasonics, Low Frequency Pitch-Catch Ultrasonics, Resonance and Acoustic Impact.

Table A-1 lists the NDT techniques for both debond and water detection which were chosen for laboratory evaluation as a result of the qualitative evaluations in this Appendix.

TABLE A-1 SUMMARY OF QUALITATIVE EVALUATIONS OF NDT TECHNIQUES

INSPECTION REQUIREMENT	PANEL COMPOSITION		X-RAY RADIOGRAPHY		NEUTRON BACKSCATTER COUNTER	HIGH FREQUENCY PITCH-CATCH ULTRASONICS			LOW FREQUENCY PITCH-CATCH ULTRASONICS	ACOUSTIC RESONANCE	EDDY SONICS	ACOUSTIC IMPACT	VACUUM DISPLACEMENT
	FACING	CORE	TRANSMISSION	BACKSCATTER		TIME	PHASE	AMPLITUDE					
DEBOND DETECTION	FIBERGLASS	HONEYCOMB	NA	NA	NA	NA	NA	NA	X	X	NA	X	X
	FIBERGLASS	BALSAMOOD	NA	NA	NA	NA	NA	NA	X	X	NA	X	X
	FIBERGLASS	FOAM	NA	NA	NA	NA	NA	NA	X	X	NA	X	X
	METAL	HONEYCOMB	NA	NA	NA	NA	NA	NA	X	X	X	X	X
	METAL	BALSAMOOD	NA	NA	NA	NA	NA	NA	X	X	X	X	X
	METAL	FOAM	NA	NA	NA	NA	NA	NA	X	X	X	X	X
WATER DETECTION	FIBERGLASS	HONEYCOMB	X	X	X	X	X	X	X	X	NA	X	NA
	FIBERGLASS	BALSAMOOD	X	X	X	X	X	X	X	X	NA	X	NA
	FIBERGLASS	FOAM	X	X	X	X	X	X	X	X	NA	X	NA
	METAL	HONEYCOMB	X	X	X	X	X	X	X	X	X	X	NA
	METAL	BALSAMOOD	X	X	X	X	X	X	X	X	X	X	NA
	METAL	FOAM	X	X	X	X	X	X	X	X	X	X	NA

NA = Not Applicable
X = Selected for Laboratory Evaluation

APPENDIX B

LABORATORY EVALUATION

- . Test Sample Preparation and
Laboratory Procedure
- . Debond Detection
- . Water Detection

TEST SAMPLE PREPARATION AND LABORATORY PROCEDURE

As the initial step in the laboratory evaluation procedure, various shelter sandwich panel types were identified and test sample panels were selected. A Bare Base shelter, and other individual panels, supplied by the Air Force Civil Engineering Center provided a wide range of panel materials and compositions which were used in the selection of test samples for use in the evaluation of commercially available instrumentation. The test samples contained naturally occurring debond conditions which were used as standard "defects" for instrumentation evaluations.

To determine which panel areas from the Bare Base shelter would be selected for use as laboratory test samples, 100% of all exterior panel surfaces were inspected with High Frequency Pitch Catch Ultrasonics. These panels were aluminum face sheet-to-foam core compositions. An arbitrary signal level was assigned to the portion of the A-scan display of the ultrasonic instrument (corresponding to the facing-to-core, or adhesive layer, interface) to represent the bonded condition. The total panel surface was then examined by this technique and the relative changes in this signal were monitored. The indications observed ranged from high amplitude reflections over isolated 1" diameter areas to continuous moderate amplitude noise from 10" diameter areas.

Upon completion of the ultrasonic inspections, sections of panels representing the typical variations in ultrasonic results were removed from the shelter. Portions of the selected sections underwent additional testing using X-radiography. The radiographic results for a typical 5" x 9" section of aluminum-to-foam panel section are presented in Figure B-1. This sample had been selected for evaluation because of high-amplitude debond indications and a generally high overall noise level observed during the ultrasonic inspection as debonds. Identification of the darker areas as voids in the adhesive layer which joins the face sheet to the core material was provided by a peel test of the sample. The peel test results, shown in Figure B-2, directly correlate with both ultrasonic and radiographic results. These preliminary results established the nature of inspection conditions which could affect subsequent technique evaluation. The naturally-occurring voids



Figure B-1 TRANSMISSION X-RADIOGRAPH OF METAL-TO-FOAM
SHELTER PANEL SAMPLE



Figure B-2 PEEL TEST RESULTS FOR RADIOGRAPHED PANEL SAMPLE

in the adhesive layer of metal-to-foam panels provided a standard debond reference for the evaluations of other test instrumentation. This reference assured the validity of the relationship between an instrument response and defect presence. Since instrument response to, or resolution of, a defect condition establishes the inspection acceptance, or rejection criteria, such a correlation must necessarily be determined to establish inspection reliability.

Test Panels

Four types of composite test panels were used as standards for evaluation of inspection equipment. One set of panels consisted of aluminum face sheet with foam cores. The face sheet thickness of these samples ranged from approximately 0.020" to approximately 0.045", with two different foam core types. Naturally occurring defects were present in the form of 2" to 3" diameter debond areas located between the face sheet and the adhesive layer. A second set of test panels consisted of 0.045" aluminum face sheets with a 1-3/4" thick resin-impregnated paper honeycomb core. These panels contained areas of missing adhesive of 1/2" to 2" in diameter which simulated debond conditions for evaluations of inspection equipment which operated by direct mechanical contact with the test panel surface. Another set of test panels consisted of a 0.020" aluminum face sheet and a 3/4" balsawood core. This panel set contained both natural and simulated defect conditions. The fourth set of panels consisted of approximately .030" fiberglass face sheets and a .750" thick impregnated honeycomb core. These panels were 4' x 8' in size and contained 1" to 3" diameter defect areas simulating debond at the fiberglass to adhesive interface. This set of panels was used to evaluate the capability of inspection equipment for defect detection in nonmetallic panels.

Test Procedure

The objective of the equipment evaluations was to determine instrument capability for detection of defect conditions. This was accomplished by inspecting each of the four types of panel samples described above to establish instrument sensitivity to various structural effects such as face sheet material, face sheet thickness changes, and variation of core materials. The tests were conducted in both vertical and horizontal positions to simulate realistic inspection conditions.

In addition to instrument sensitivity to debond, other instrument parameters observed included "noise" effects, resolution scan rates, accuracy, ease of operation, and the capability for detection of water.

"Noise" can be defined as any signal which interferes with the capability to detect defects. A defect has been classified for this investigation by the inspection specification as any localized debond area of 2" diameter, or greater.

Noise in nondestructive testing generally falls into one of two categories: electrical noise or test material noise. As measures to minimize electrical noise had been taken in performance of these evaluations, the noise conditions which are discussed below are attributed solely to interference resulting from the actual test material. Material noise in sandwich panel inspections is generated by variables such as surface roughness, edge effects and surface nodal conditions, naturally occurring voids in the adhesive layers, and adhesive layer thickness variations.

The resolution capabilities were determined by evaluating instrument response to debond areas of from 1/2" to 3" in diameter in the test panel sets described. Scan rates, inspection accuracy, and ease of operation were evaluated by determining the continuity and speed of manipulation of the inspection instrument sensing device while maintaining sensitivity to pre-determined 2" diameter debond areas in the test panels. Potential capabilities of the instrumentation for detection of water were evaluated by introducing water into the test panels. Approximately 3 ml to 6 ml of water was injected into paper honeycomb cells of a 2" core material which had 0.045" aluminum face sheets. Fiberglass-honeycomb panels were prepared in a similar manner, thereby providing simulated water defects of 50 to 100% through panel ranges for the honeycomb panels. 10 - 50 ml of water were introduced into debond areas between face sheets and adhesive layers in aluminum-to-foam panels simulating realistic water defect conditions observed in the field. These prepared panels enabled evaluations of inspection instrument capabilities for water detection.

DEBOND DETECTION

This part of Appendix B presents the results of laboratory evaluations performed to determine the capability of NDT methods selected on a qualitative basis for detection of debonds in shelter sandwich panels. The methods evaluated were Eddy Sonics, Vacuum Displacement, Resonance, Acoustic Impact and Low Frequency Pitch-Catch Ultrasonics.

Eddy Sonics

The Eddy Sonics technique was evaluated for debond detection capability using the Shurtronics Mark IIB Harmonic Bond Tester shown in Figure B-3. A modified version of the instrument was found capable of debond detection in panels with metal facing sheets. The method underwent further laboratory and field evaluations and the results are presented in detail in Section V of the body of this report.

Vacuum Displacement

The Vacuum Displacement technique was evaluated for debond detection capability using the Mason Associates Composite Bond Analyzer (CBA) illustrated in Figure B-4.

A well-bonded laminate is a more rigid test surface and the resulting localized displacement will be less than that which would result from a less-rigid debond area. The instrument detects debond in composite materials by application of a partial vacuum to a localized surface area of the material and measurement of any resulting displacement of that localized area. Vacuum application and displacement detection is accomplished by a single hand-held transducer. The vacuum is applied to a 3/4" diameter area and displacement is measured by a piezoelectric crystal which detects the mechanical deformation of the test surface converting it to an electrical signal for meter readout. Bond quality is determined by comparison of the meter reading with results obtained from a similar test sample of known quality.

Four types of composite test panels were used in evaluation of the CBA: 0.050" aluminum facing sheet with 2" thick paper honeycomb core; 0.030" aluminum face sheet with 1-3/4" thick foam core; 0.020" aluminum face sheet with 1/2" thick balsa core, and 0.060" fiberglass face sheet with 3/4" thick



Figure B-3 EDDY SONICS INSPECTION INSTRUMENTATION

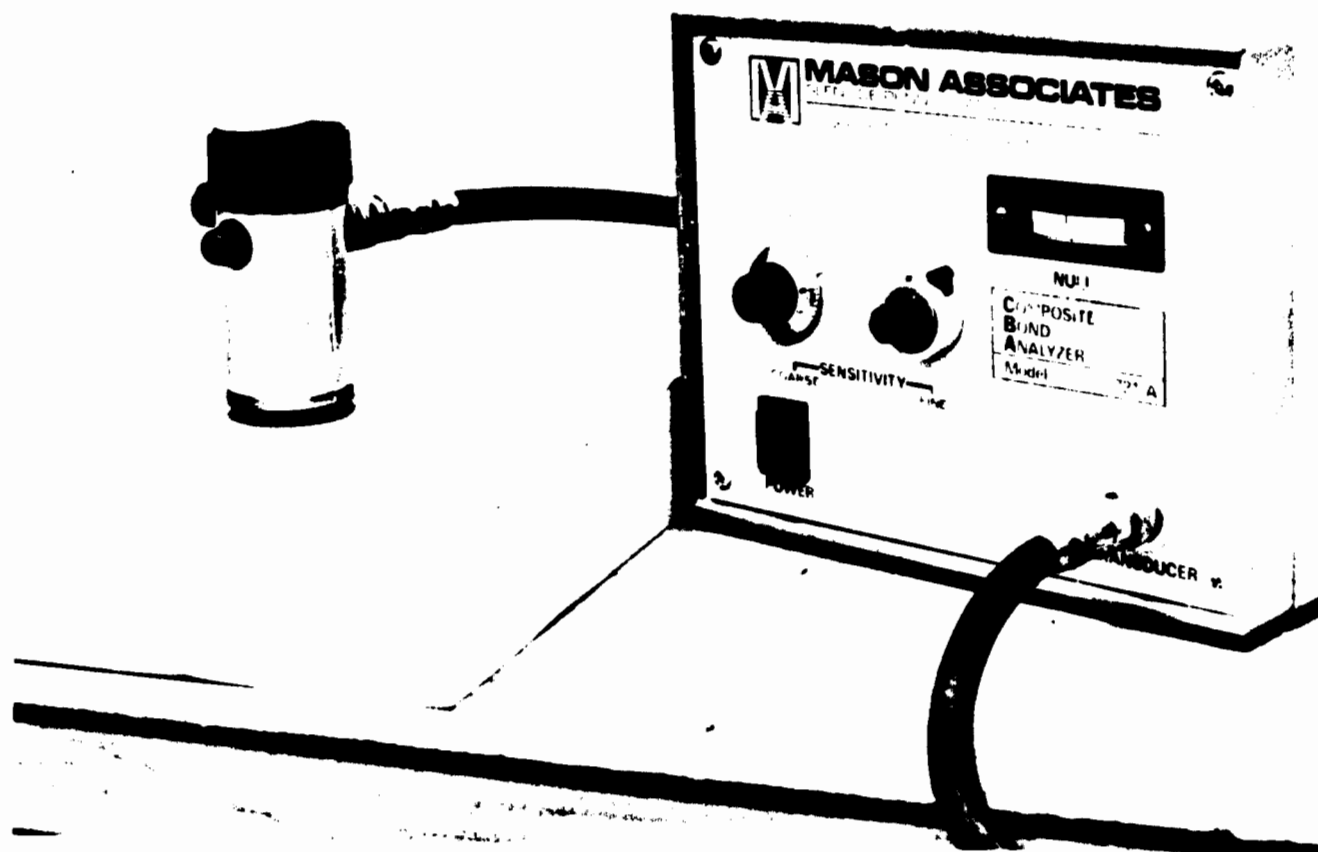


Figure B-4 VACUUM DISPLACEMENT INSPECTION INSTRUMENTATION

paper honeycomb core. Each test panel contained naturally occurring debonds.

The CBA reliably detected 2" and 3" diameter debonds in the foam core panels with 0.020" and 0.040" aluminum face sheets. Inspection results with foam core panels with thicker face sheet (0.050") were not reliable, however. The reduced sensitivity to debond in these panels is believed to be due to the fixed transducer area over which the vacuum is applied. For each panel type inspected, the instrument was observed to be sensitive to variations in test surface condition. Reliable inspection results would, therefore, depend upon uniformity of reference and inspection panel surfaces, freedom from surface blemishes (scratches, dents, etc.) and any other physical condition which would affect application of a uniform vacuum.

The sensitivity of the instrument to variations in vacuum efficiency required a slow and tedious scan rate of about 0.5 square feet per minute. A scan rate of approximately 1 square foot per minute enables detection of a 1-1/2" diameter near side debond in a foam core panel with 0.020" thick face sheet. However, at this scan rate, some false indications were also observed. The scan rate is inherently limited by the nature of application of a vacuum to perform the bond test. A horizontal force of 3 lbs. was required to pull the transducer along a 3/4" path on a painted aluminum face sheet. This measurement was taken by applying the force near the face of the transducer and does not include any vertical force component which would be required to maintain surface contact during hand scanning.

The evaluation of the Composite Bond Analyzer for detection of debonds in shelter sandwich panels has resulted in the conclusion that the instrumentation is not suitable for this inspection application. Poor signal-to-noise due to test surface variations which affect vacuum efficiency, high sensitivity to face sheet material thickness variations, and difficult transducer manipulation resulting in very slow scan rates are the major disadvantage of this technique. Additionally the instrument was also found to need extensive hardening before practical field evaluations could be undertaken.

Resonance

The Resonance technique for use in structural defect detection operates on the principle that a material can be induced to vibrate at a fundamental resonant frequency in response to application of a broad band of acoustic

frequencies. This technique was evaluated for its capability to detect debond in shelter sandwich panels using the Electro-Physics Soni-Bond Model 5B-1000, illustrated in Figure B-5. This instrument generates acoustic vibrations in the range from 20kHz to 100kHz using a piezoelectric transducer and monitors the acoustic response of the material. The acoustic vibrations are introduced into the material by direct contact of the transducer to the material surface, using a liquid couplant. The test material in the area of transducer contact responds to the induced acoustic vibrations by vibrating at a resonant acoustic frequency determined by the elastic properties of the material. The amplitude of the resonant vibration is related to the structural integrity of the material in that local area. The transducer senses the resonant response which is processed by a built-in frequency spectrum analyzer. The resonant frequency is identified and displayed on a CRT presentation of an impedance bridge current vs. frequency. The bridge current is proportional to the amplitude of the resonant vibration and, since the amplitude of the resonant vibration is directly related to the elastic properties of the test material, this electrical signal is used as a measure of the structural integrity of the test material. The electrical signal is also used to operate a meter to provide quantitative numerical results or to activate an audible alarm. The instrument was evaluated for debond detection using an aluminum-to-honeycomb panel (0.050" face sheet and 1-3/4" thick resin-impregnated-paper honeycomb core) and an aluminum-to-balsawood panel (0.020" face sheet and 0.5" balsawood core). Debonds in the honeycomb panel were 1/2" to 2" in diameter and the balsawood panel contained naturally occurring debonds and two artificial debond areas created by removal of core material. These panels were scanned using the 3/4" diameter transducer provided with the instrument. (Other sizes of transducers are available from the manufacturer.) Inspection of the test panels for debond demonstrated excellent signal-to-noise relationships. CRT presentation of the bond condition in the honeycomb panel is shown in Figure B-6a. The CRT presentation of the 2" near-side debond area in the same panel is shown in Figure B-6b. Similar results were obtained from inspection of the balsa core panel. Sensitivity of the technique to far-side debond was demonstrated. However, signal-to-noise was substantially reduced.

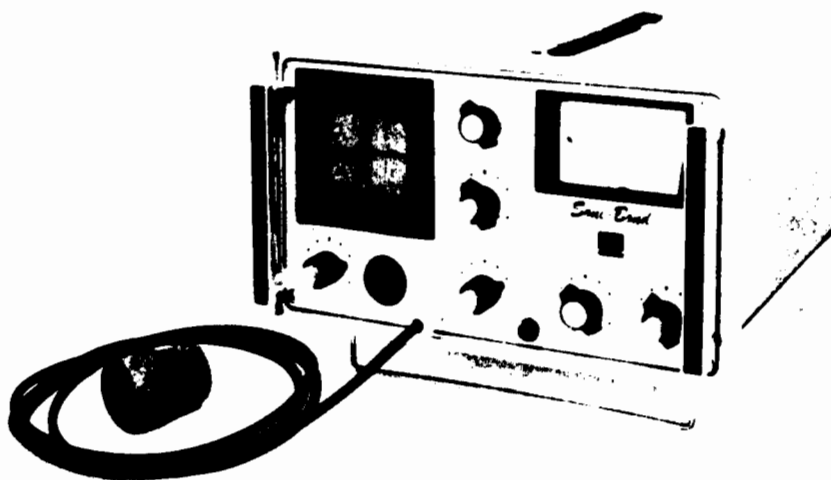
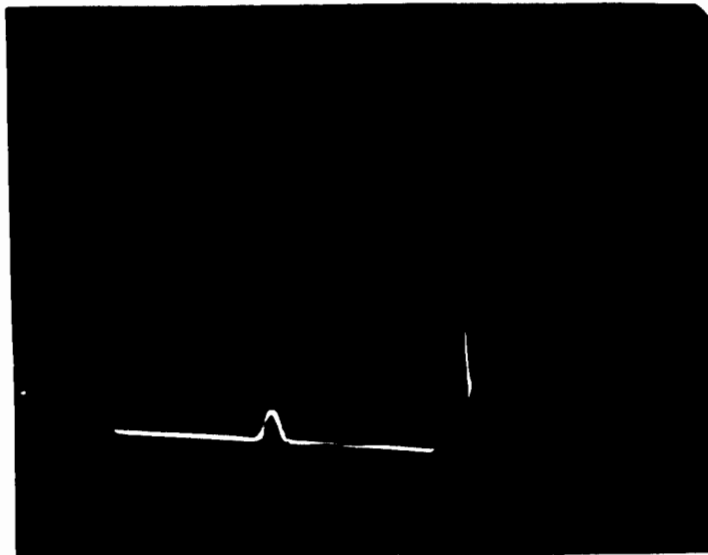
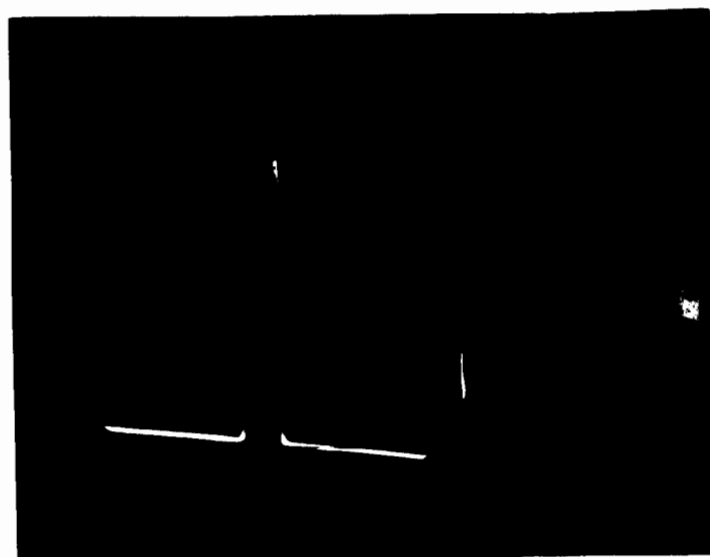


Figure B-5 RESONANCE INSPECTION INSTRUMENTATION



(a) BOND



(b) DEBOND

Figure B-6 CRT DISPLAY OF BOND AND DEBOND CONDITIONS
FROM RESONANCE INSTRUMENTATION

Scan rates for this technique were based upon reliable detection of 2" diameter debonds. To maintain this defect sensitivity, a light, smooth, even scan rate of approximately 200 square feet/hour was required for both panels. This rate was determined using the CRT display for defect detection. An increased rate of 250 square feet per hour can be expected using the audible alarm as the defect condition detector, due to the faster response of the alarm circuit. Scan rates can also be increased by selection of a larger diameter transducer. However, defect sensitivity decreases with increase in transducer diameter. With the 3/4" diameter transducer, surface coordinates of the 2" debond in the honeycomb panel could be measured within $\pm 1/4"$.

The Soni-Bond instrument demonstrated debond detection capability for inspection of laminate material. However, the necessity for use of a liquid couplant reduces inspection reliability and results in scan rates below the requirements for use in shelter panel inspection. The technique was, therefore, not recommended for further evaluation.

Acoustic Impact

The Acoustic Impact technique can use a vibrating crystal to drive a piston which mechanically strikes the surface of a material exciting the structure acoustically. The structure responds to the induced acoustic vibrations by vibrating at its fundamental resonant frequency. The amplitude of these resonant vibrations is proportional to the elastic properties of the material. As structural defects in the material affect these elastic properties, measurement of the amplitude of resonance can be used as an indicator of structural properties of the material.

The instrumentation used to evaluate the Acoustic Impact technique for debond detection in shelter sandwich panels is shown in Figure B-7. The response of the test material to the repetitive tapping of the piston is monitored by a vibration pick-up in contact with the sample which converts the mechanical response to an electrical signal which is analyzed for frequency spectrum content and displayed on an oscilloscope.

Sample panel sections representing each of the composite panels used in shelter construction were inspected by the Acoustic Impact technique.

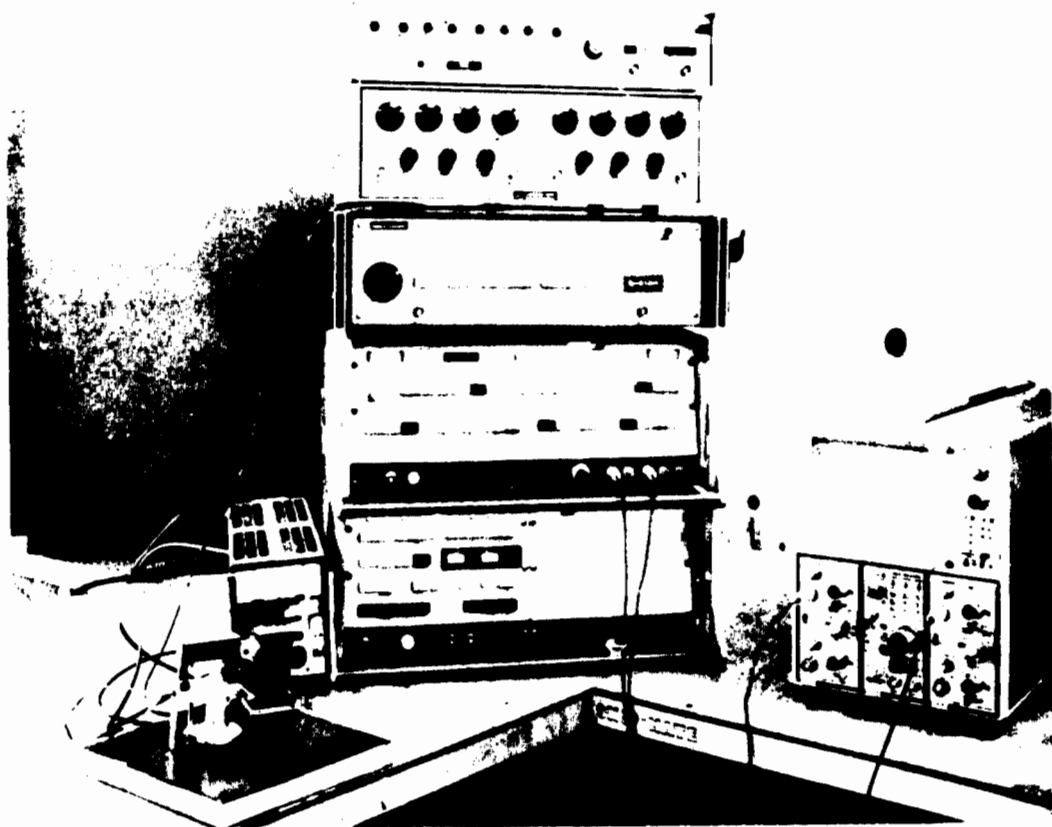


Figure B-7 ACOUSTIC IMPACT INSPECTION INSTRUMENTATION

Two-inch diameter debond areas in aluminum-to-foam and aluminum-to-honeycomb panels were reliably detected by this technique. Signal-to-noise differentiation of 5:1 between responses from bond and debond was readily obtained for panels with 0.030" thick aluminum face sheet and a 2" foam core. The bond condition for this panel configuration is illustrated in Figure B-8a. This oscilloscope photograph shows that portion of the frequency spectrum which includes the high amplitude resonance frequency response typical of a structurally intact portion of the panel. The presence of a debond condition, as shown in Figure B-8b, illustrates the reduction in received acoustic energy resulting from the structural defect.

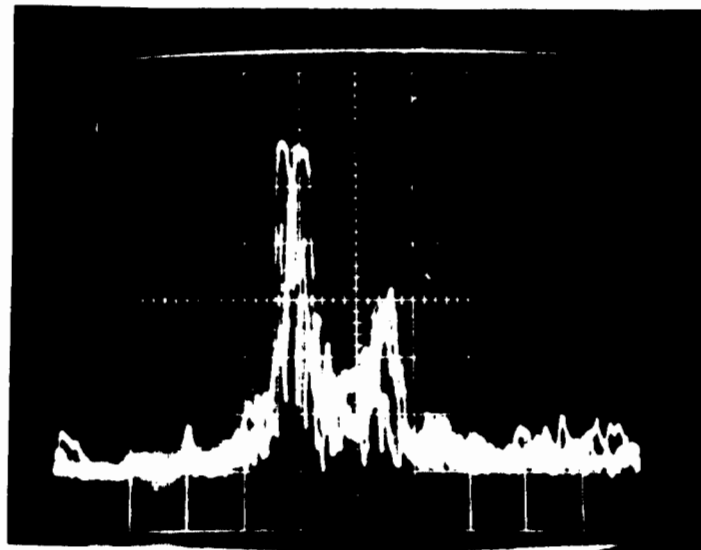
While providing excellent signal-to-noise, reliable debond sensitivity, and eliminating the need for liquid couplants, the Acoustic Impact technique for inspection of composite materials for structural defects remains in the developmental stage and was determined impractical for current application to field inspection requirements for shelter panels, due to the successful application of the Eddy Sonic technique to the inspection problem.

Low Frequency Pitch Catch Ultrasonics

The Low Frequency Pitch Catch Ultrasonics technique was evaluated in the laboratory. The evaluation demonstrated the capability of this technique for reliable detection of debond in fiberglass facing sheet samples. The technique was, therefore, considered for further evaluation. The technique is discussed in detail in Section V of the body of this report.

Summary

The nondestructive testing techniques evaluated in the laboratory for debond detection capability were Low Frequency Pitch-Catch Ultrasonics, Acoustic Resonance, Eddy Sonics, Acoustic Impact, and Vacuum Displacement. The results of these evaluations are summarized in Table B-1 of this Appendix which follows the discussion of laboratory evaluation of techniques for moisture detection.



(a) BOND



(b) DEBOND

Figure B-8 OSCILLOSCOPE PRESENTATION OF ACOUSTIC IMPACT
RESULTS FOR BOND AND DEBOND

MOISTURE DETECTION

This part of Appendix B presents the results of laboratory evaluations performed to determine the applicability of NDT techniques selected on a qualitative basis for practical use in the detection of water in shelter sandwich panels. The techniques evaluated were Eddy Sonics, X-Radiography, Neutron Backscatter, both High Frequency and Low Frequency Pitch-Catch Ultrasonics, and Acoustic Impact.

Eddy Sonics

The Eddy Sonics technique was evaluated for the capability to detect water in shelter sandwich panels. The technique was successful in laboratory tests and was selected for further evaluation. This technique is discussed in detail in Section V of the body of this report.

X-Radiography

X-rays are a form of radiant energy, as is light, which are produced whenever fast traveling electrons collide with matter. They are distinguished from other radiant energy by their wavelengths (typically, 1/10,000 that of visible light) which enable them to penetrate materials which ordinarily reflect or absorb visible light. X-rays also produce a photographic effect on sensitized film or paper. The photographic image resulting from the passage of X-rays through a material and onto sensitized film or paper is called a radiograph. Properties of the material thus radiographed can then be interpreted by observation of the variations in exposure density recorded on the film.

X-Radiography was evaluated for its capability to detect water in shelter sandwich panels. Transmission and backscatter modes, film and paper processes, and portable and permanently installed X-ray generating equipment were employed during this investigation. The radiographs obtained were made at approximately 35 kilovolt peak (KVP) potentials, with 4 milliamp (ma) tube current, and 5 to 10 second exposure times. The test sample panels included metal-to-foam, metal-to-honeycomb, and fiberglass-to-honeycomb sections removed from an available shelter. These samples were first radiographed in the as-supplied condition to provide a control reference for subsequent radiographs made after having introduced water between the panel face sheets to simulate the water defect condition.

The sensitivity of the Transmission Radiography technique to detection of voids in the adhesive layer of metal-to-foam panels has already been documented and discussed in the Sample Preparation section of this appendix. The results of Transmission Radiography of a section of the same panel composition with water present in a series of 0.125" steps machined into the foam are presented in Figure B-9. In this radiograph, the thickest water layer is .125" thick and differentiation of this resulting image density from background density relies heavily upon the skill and training of the film reader. This situation results in limitation to the reliability of the inspection technique for use in the inspection of this panel composition. The presence of water in the individual cells of a honeycomb panel is somewhat more readily evident as shown in Figure B-10. This transmission radiograph illustrates improved signal-to-noise resulting from the increase of water layer thickness to 3/4", or a full honeycomb cell. (This radiograph, as was the radiograph shown in the previous figure, was made using KODAK INDUSTREX Instant 600 Paper and processed using the KODAK INDUSTREX Instant Processor Model P-1 paper processor. While offering a major advantage of reduction in processing time to 10 seconds, the paper method still requires the darkroom and chemicals limitation of any photographic, (i.e., light-sensitive) operation.

Backscatter X-Radiography was evaluated for use in the detection of water in shelter sandwich panels. Some of the X-rays which are reflected by more dense material resulting in less exposed areas on a transmission radiograph can be monitored by placing the film on the same side of the sample as the X-ray source. The resulting image is the inverse of a transmission radiograph in that the more dense material now is represented by darker areas on the radiograph caused by an increased intensity of reflected X-rays. The backscatter radiography results for detection of water in a metal-to-honeycomb panel sample are shown in Figure B-11. The X-rays were obtained from a 150 KV Beryllium window source tube. Using Kodak Type M film, this exposure was made at 150 KVP with a tube current of 4 ma for 1 minute. A 0.060" copper filter was used to absorb soft, or longer wavelength, incident X-radiation. Water defect presence was

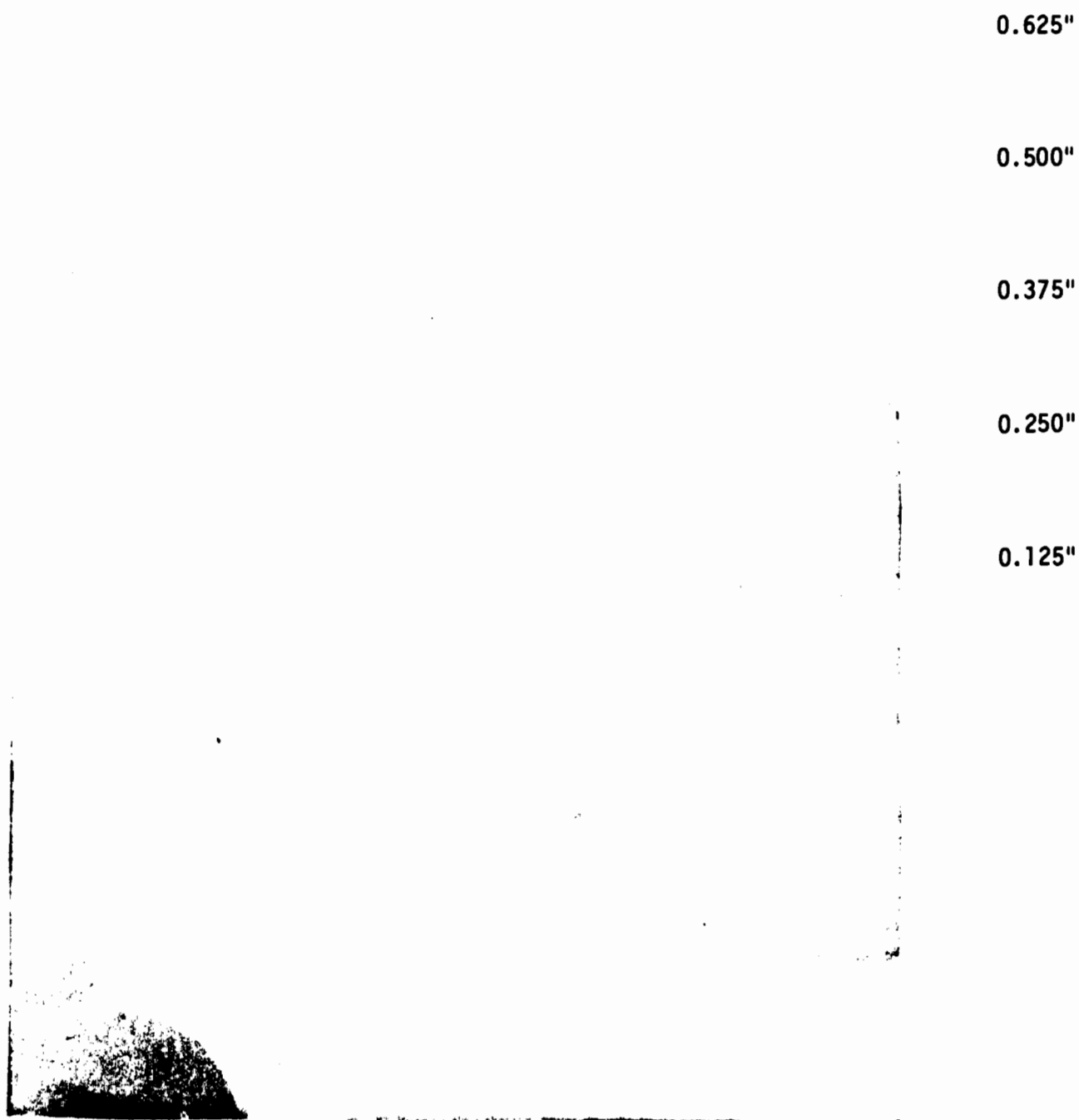


Figure B-9

TRANSMISSION X-RADIOGRAPH OF METAL-TO-FOAM
SAMPLE WITH .125" WATER LAYERS

FULL
CELL

PARTIALLY-FILLED
CELLS

HALF-FILLED
CELLS

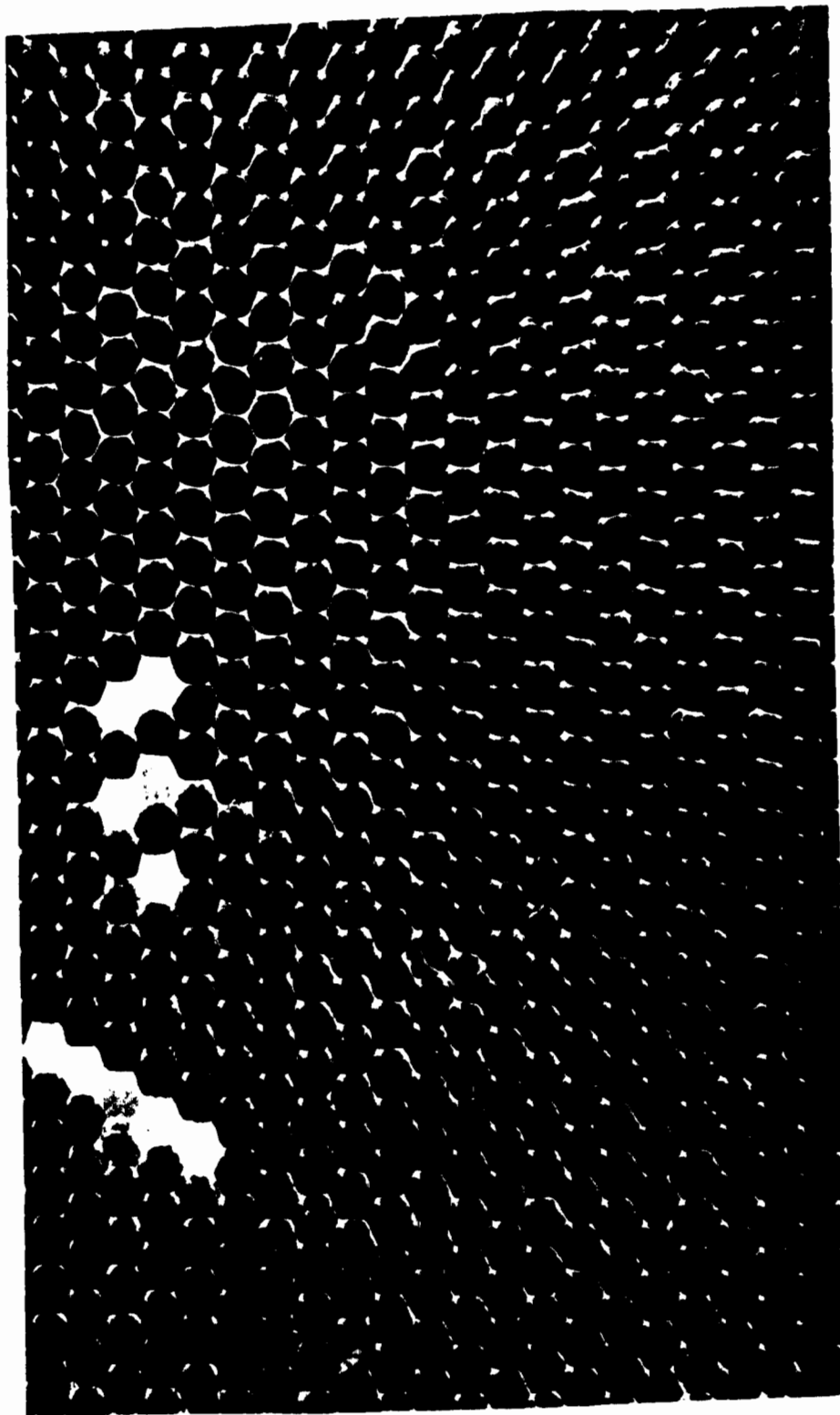


Figure B-10 TRANSMISSION X-RADIOGRAPH OF FIBERGLASS-TO-HONEYCOMB
PANEL SAMPLE WITH WATER IN SELECTED CELLS

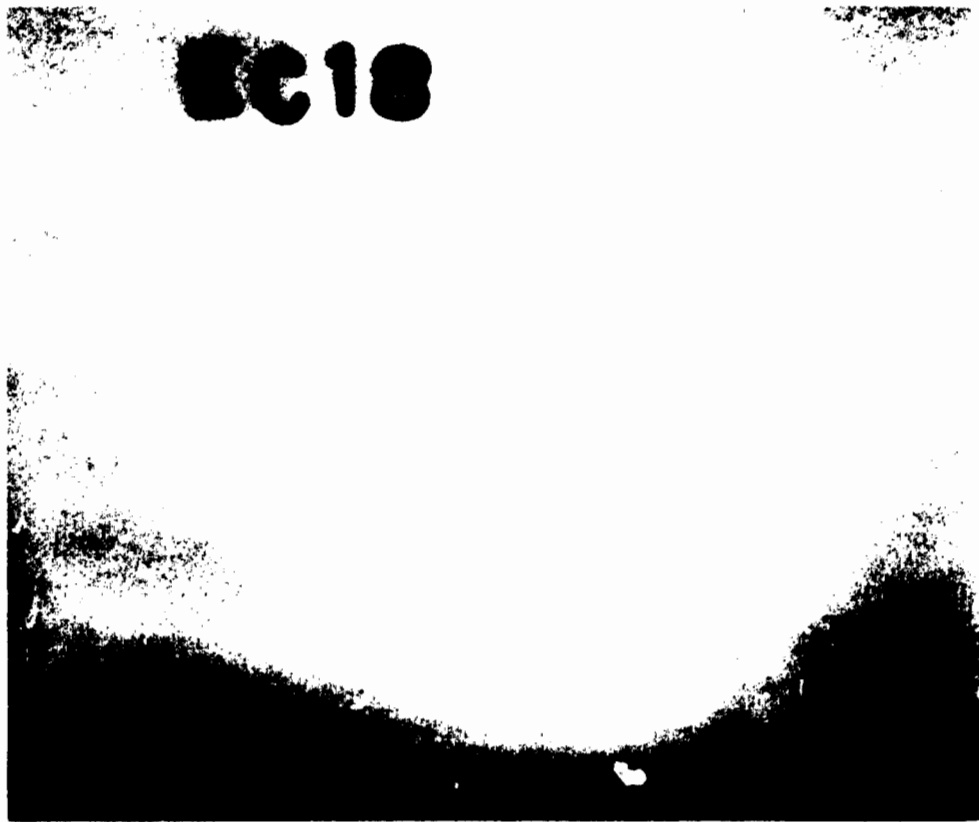


Figure B-11 BACKSCATTER X-RADIOGRAPH OF METAL-TO-HONEYCOMB
PANEL WITH SIMULATED WATER DEFECT

simulated for this exposure by placement of a 50 ml beaker full of water in back of the panel sample in the experimental arrangement which is shown schematically in Figure B-12. The defect condition itself represented a 3" diameter water column approximately 4" deep which exceeds the actual inspection requirements. From the radiograph of this sample it is apparent that the backscatter principle which encouraged this evaluation inherently limits the sensitivity of the technique. This is due to the fact that all of the incident X-rays strike some target material (cassette, sample, support structures, etc.) and thus produce some scatter. The wavelengths of much of the incident X-radiation are increased by this scattering, and, hence, are softer, but care must be taken to adequately filter this radiation to maintain sufficient signal-to-noise which provides image contrast in the final radiograph. The results presented in the radiograph emphasize this limitation.

The results of both Transmission and Backscatter X-Radiography presented herein demonstrate the capability of this NDT technique for detecting water in shelter sandwich panels. The transmission mode offers the better signal-to-noise capability. However, it also imposes the greatest practical limitation of this technique in being a two-sided test. The backscatter mode is seen to impose limitations which are the exact inverse. Both modes of operation are further limited by the necessity of support facilities which are impractical for the field application of this technique to the inspection of shelter panels. For these reasons, X-Radiography was not recommended for further evaluation as a field inspection technique.

Neutron Backscatter

As a nondestructive testing technique, Neutron Radiography differs from X-Radiography in that the penetrating radiation consists of neutrons having high kinetic energies. These so-called "fast" neutrons are generated by the collision of X-rays or gamma rays with the atoms of a few of the lighter elements. As these fast neutrons pass through a material, they collide with the atoms of the lighter elements present in the material, giving up some of their kinetic energy in the process, and are scattered in various directions as a result of the collision. The scattered neutrons, now slowed to kinetic energies closer to the average kinetic energy of the material, are said to have been thermalized, and can be monitored as thermal

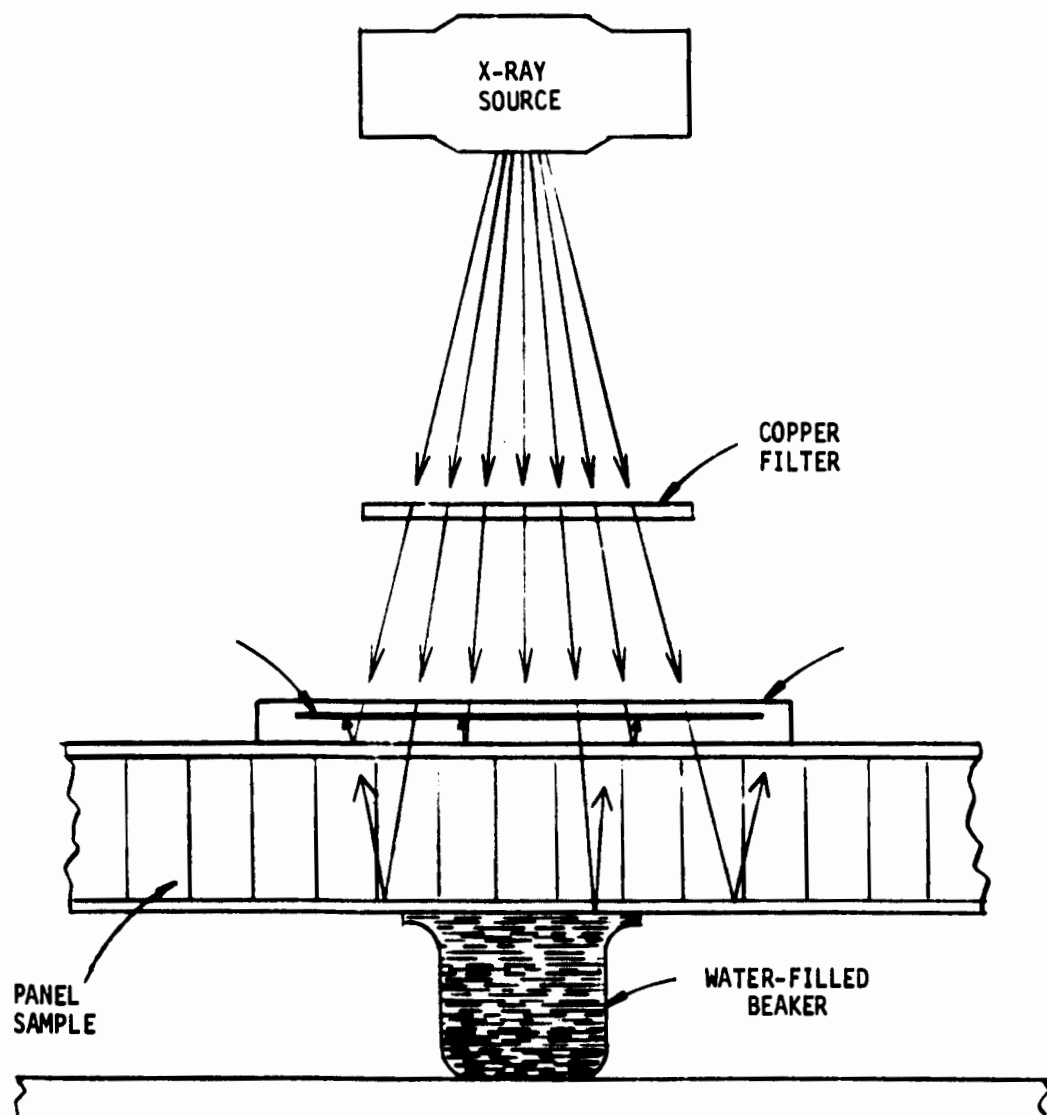


Figure B-12 SCHEMATIC REPRESENTATION OF LABORATORY ARRANGEMENT
USED TO OBTAIN X-RAY BACKSCATTER RADIOGRAPH

neutrons. In the Neutron Backscatter technique, the thermal neutron detector is located on the same side of the test material as the source of the fast neutrons. In the collisions of fast neutrons with lighter elements in the test material, a statistical percentage of the neutrons are scattered back toward the source, and these are detected as a measure of the proportion of light elements contained in the material.

The instrumentation evaluation in the laboratory for determination of the capability of this technique to detect water in shelter sandwich panels was the Soil Test, Inc., Nuclear Moisture Density Gage Model NIC5-DT, illustrated in Figure B-13. For this inspection application, the hydrogen atom of the water molecule provides the light element target which slows and scatters the incident fast neutrons. The fast neutrons are generated by the interaction of gamma radiation from a shielded source with a beryllium window from which they enter the test material. The principle of operation and the experimental arrangement used for this evaluation are presented schematically in Figure B-14. As shown in the figure, some of the neutrons are thermalized and scattered back to the detectors in the instrument. A clock circuit in the instrument enables the measurement of the rate of backscattered thermal neutrons. This rate is converted to an electrical signal which provides a meter readout. The meter on this instrument has been calibrated to read in a moisture density analog of lbs./ft.³ of water in the sample material. (Other commercially available instrumentation provides a digital readout of count rate which must be converted by the operator using calibration charts developed for different base materials.)

Metal-to-foam and fiberglass-to-honeycomb panel samples were used to evaluate this technique for water detection. The instrument was found incapable of differentiating water present in the amounts considered as defect conditions from dry samples of the same composition. These results are due to a combination of the large neutron flux density allowed to penetrate the test material and the extensive penetrating power of the fast neutrons which effectively interrogate a 2 or 3 cubic foot volume adjacent to the instrument. This situation, therefore, does not enable inspection of the panel material alone, but also includes the effect of the material behind the sample. These results have determined that the



Figure B-13 NEUTRON BACKSCATTER MOISTURE DENSITY
INSTRUMENTATION

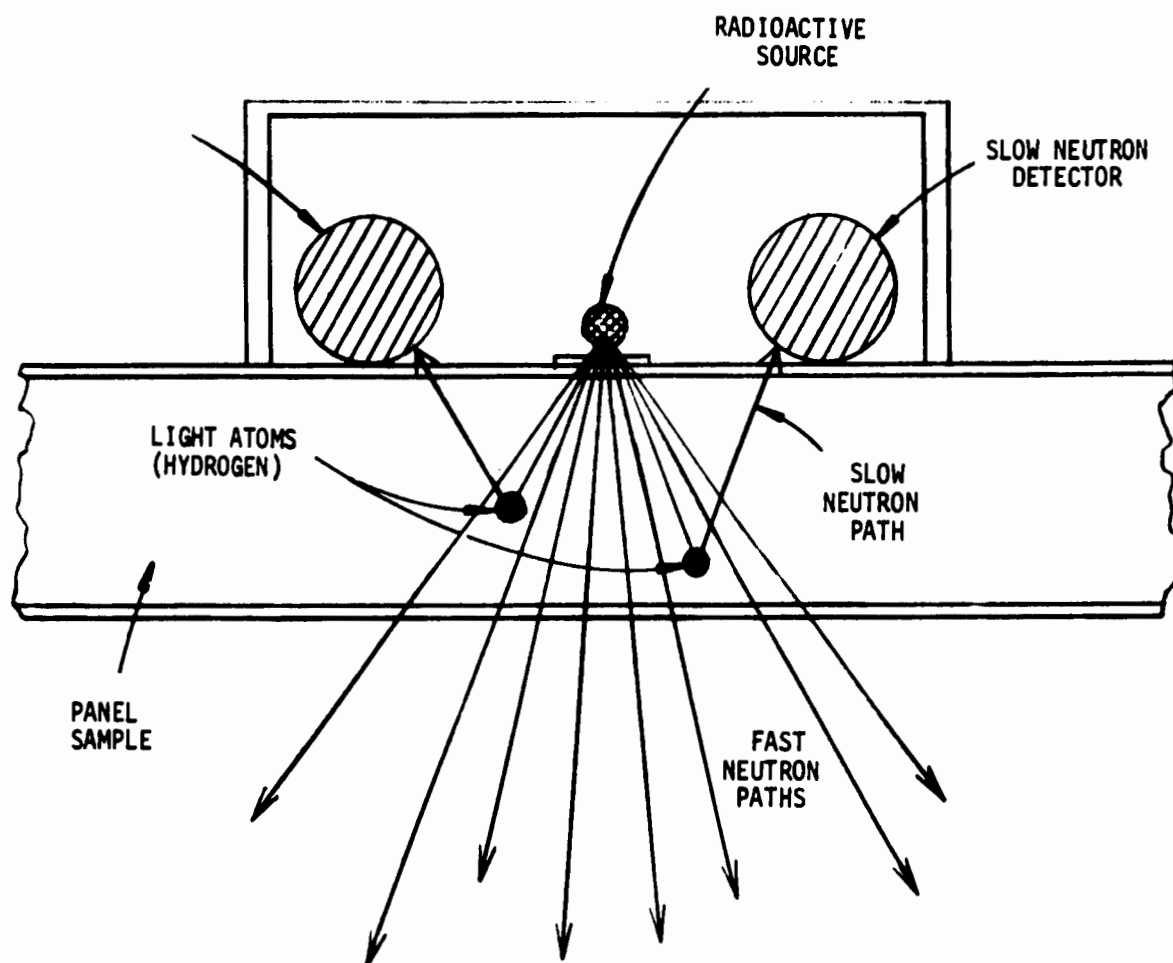


Figure B-14 SCHEMATIC REPRESENTATION OF
NEUTRON BACKSCATTER PRINCIPLE EMPLOYED BY
MOISTURE DENSITY GAGE

use of Neutron Backscatter techniques is not applicable to shelter panel inspection requirements and the technique was not recommended for further evaluation in this program.

High Frequency Ultrasonics

The High Frequency Ultrasonics technique was evaluated in both Pitch-Catch and Pulse-Echo modes in the laboratory for capability to detect water in shelter sandwich panels by monitoring the time, phase, and amplitude characteristics of the received ultrasonic energy. The time and amplitude technique was successful in this evaluation and was selected for further evaluation. The technique is discussed in detail in Section V of the body of this report.

Low Frequency Pitch-Catch Ultrasonics

The Low Frequency-Pitch Catch Ultrasonics technique was evaluated in the laboratory to determine the capability to detect water in shelter sandwich panels. The (principle of operation of the test instrumentation is described in Section V.) Low Frequency Pitch-Catch Ultrasonics instrumentation was found capable of change in phase of the received sound wave. The test instrument was, therefore, recommended for additional evaluation for application to inspect this panel material. For the metal-to-honeycomb and fiberglass-to-honeycomb panel sample, the instrumentation detected variations in the received sound wave, but it was incapable of differentiating between debond and water as sources of the observed variations. The technique was therefore not recommended for application to inspection of these panel compositions for detection of water.

Acoustic Impact

The Acoustic Impact technique was evaluated in the laboratory to determine the capability of this technique to detect water in shelter sandwich panels. The theory of operation of this technique is described in the section of this appendix which presents the results of investigation of this technique for debond detection capability. Two to one signal-to-noise differentiation was obtained between dry and water-containing samples of metal-to-honeycomb, metal-to-foam, and fiberglass-to-honeycomb panels.

However, as previously stated, the existing instrumentation for application of this technique to practical field inspection of shelter panels cannot be pursued without extensive development and field-hardening of the basically experimental instrumentation available at this time. This technique was therefore not recommended for further evaluation under this program.

Summary

The nondestructive testing techniques evaluated in the laboratory for water detection capability have been Eddy Sonic, X-Ray Radiography, Neutron Backscatter, High Frequency and Low Frequency Pitch-Catch Ultrasonics and Acoustic Impact.

The results of these evaluations are summarized in Table B-1 of this Appendix.

TABLE B-1 SUMMARY OF LABORATORY EVALUATIONS OF NDT TECHNIQUES

INSPECTION REQUIREMENTS	PANEL COMPOSITION		X-RAY RADIOGRAPHY		NEUTRON BACKSCATTER COUNTER	HIGH FREQUENCY PITCH-CATCH ULTRASONICS			LOW FREQUENCY PITCH-CATCH ULTRASONICS	ACOUSTIC RESONANCE	EDDY SONICS	ACOUSTIC IMPACT	VACUUM DISPLACEMENT
	FACING	CORE	TRANSMISSION	BACK-SCATTER		TIME	PHASE	AMPLITUDE					
DEBRID DETECTION	FIBERGLASS	HONEYCOMB	NA	NA	NA	NA	NA	NA	X	*	*	*	*
	FIBERGLASS	BALSAMOOD	NA	NA	NA	NA	NA	NA	X	*	*	*	*
	FIBERGLASS	FOAM	NA	NA	NA	NA	NA	NA	X	*	*	*	*
	METAL	HONEYCOMB	NA	NA	NA	NA	NA	NA	X	*	X	*	*
	METAL	BALSAMOOD	NA	NA	NA	NA	NA	NA	NA	*	X	*	*
	METAL	FOAM	NA	NA	NA	NA	NA	NA	*	*	X	*	*
WATER DETECTION	FIBERGLASS	HONEYCOMB	*	*	*	X	*	*	X	NA	*	*	NA
	FIBERGLASS	BALSAMOOD	*	*	*	*	*	*	X	NA	*	*	NA
	FIBERGLASS	FOAM	*	*	*	*	*	*	X	NA	*	*	NA
	METAL	HONEYCOMB	*	*	*	X	*	*	*	NA	X	*	NA
	METAL	BALSAMOOD	*	*	*	*	*	*	X	NA	X	*	NA
	METAL	FOAM	*	*	*	*	*	*	X	NA	X	*	NA

NA = Technique was determined not applicable by previous qualitative evaluations (See Table A-1)

* = Technique was determined inapplicable by laboratory evaluation.

X = Technique was determined applicable for field evaluation by lab evaluation.